Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplementary Information:

Advances in Power-to-Gas Technologies: Cost and Conversion Efficiency

Gunther Glenk[1]
Harvard Business School, Harvard University
Business School, University of Mannheim
CEEPR, Massachusetts Institute of Technology
gglenk@hbs.edu

Philip Holler
Business School, University of Mannheim
philip.holler@uni-mannheim.de

Stefan Reichelstein
Business School, University of Mannheim
Graduate School of Business, Stanford University
ZEW – Leibniz Centre for European Economic Research
reichelstein@uni-mannheim.de

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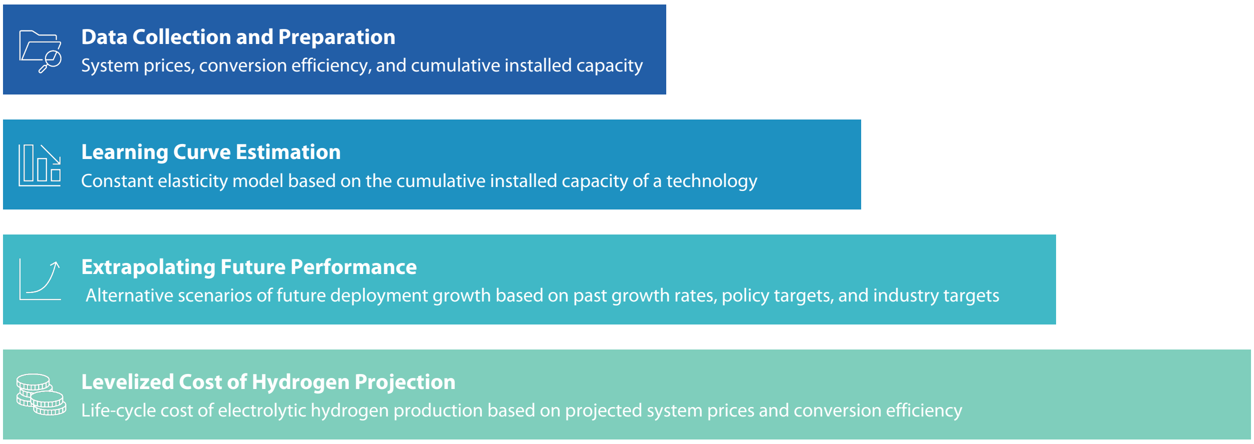
[1] Corresponding author: gglenk@hbs.edu

1 Overview

This paper provides a comprehensive assessment of the dynamics in system prices and energy efficiency for three prevalent PtG technologies: alkaline, polymer electrolyte membrane (PEM), and solid oxide cell (SOC) electrolysis. We collect and analyze global data points for system prices, energy consumption, and the cumulative installed capacity for each technology. Our regressions yield significant and robust learning curves of 83–86% for system prices and 98% for energy consumption over the past two decades. Incorporating multiple forecasts of future deployment growth, we project that, in the coming decade, all three technologies will become substantially cheaper and more energy-efficient. Specifically, the life-cycle cost of electrolytic hydrogen production is projected to fall in the range of \$1.6–1.9/kg by 2030, thereby approaching but not reaching the \$1.0/kg cost target set by the U.S. Department of Energy. Supplementary Figure 1 illustrates the main steps of our analysis.



Supplementary Figure 1. Main steps of our analysis.

2 Review of System Prices

Information on system prices is based on two earlier reviews[1;2] and a replication of the analyses performed therein. Specifically, we gathered price estimates from various sources, including manufacturers, academic articles in peer-reviewed journals, and technical reports by agencies, consultancies, and industry analysts. Academic articles were found by searching databases like Web of Science, Scopus, Google Scholar, and ScienceDirect. Keywords used in the search include ‘electrolyzer system prices’, ‘power-to-gas system prices’, and ‘electrolyzers for hydrogen production + system prices'. Industry publications and technical reports were retrieved with a Google search based on the same keywords, where we reviewed the top 100 search results.

Our review procedures retrieved 396 unique sources, which we filtered by multiple criteria to maintain quality and timeliness. We first excluded sources without clear information on system prices (60). We also excluded sources referencing other articles as original sources (66) but then traced the references back to the original sources and added those sources to the pool if they included original data. We further excluded sources without explicit references or methods for obtaining the cost estimate (94). We excluded five articles that were published before the year 2000. Finally, we excluded estimates for alkaline systems manufactured in China[3], primarily because of differences in technology and manufacturing standards[4]. To focus on recent technological advances, we also excluded sporadic estimates for alkaline systems from before the year 2000[5–7]. Most of these earlier data points are primarily based on estimates for individual large-scale capacity installations instead of observations for installations of different sizes.

Our procedure yielded 176, primarily European and North American, sources containing 264 unique observations from industry or an original review of multiple sources. Of these observations, 105 belong to alkaline electrolysis over the years 2003–2020, 81 to PEM system between 2003–2020, and 78 to SOC technology spanning the years 2011 to 2020. Since SOC electrolyzers are reversible, we include estimates for fuel cells in our sample.

For all sources, we focused on system prices that include electrolysis stacks and the balance-of-system, but exclude hydrogen compression. Where available, we also collected system prices for different system sizes. Our main analysis then includes system prices that were normalized to a system size of 1 Megawatt (MW). Yet, we also examine the potential impact of changes in the size of a PtG system on system prices. System prices reported without a system size were interpreted to refer to an average system size for the corresponding year.

We also converted any range estimates to the midpoint in the reported range. Estimates given in currencies other than $US were converted based on the annual average exchange rate of the respective year. We also adjusted historical price information for inflation using the yearly inflation adjustment factor for qualified energy resources as provided by the US Internal Revenue Service. In both adjustments, we accounted for potential differences between the year for which the prices were expressed and the year of publication of the corresponding source.

Finally, all observations of one technology were winsorized at the 5.0% level in combination with a moving time window of 3 years ranging from 1 year before to 1 year after the year in which price estimates are adjusted. Winsorization has only a minor effect on our findings for all technologies.

3 Review of Cumulative Installed Capacity

Our data set of cumulative installed capacity is primarily based on the *Hydrogen Projects Database* by the International Energy Agency[8]. The original database includes production facilities that have been commissioned worldwide since 2000 for the generation of clean hydrogen and hydrogen derivatives. Production technologies listed in the database comprise alkaline, PEM, and SOC electrolysis, coal gasification and natural gas steam reforming both with carbon capture and storage technology, and other production pathways such as biogas pyrolysis, biogas steam reforming, or biogas membrane separation. In addition, the database also includes facilities where the type of electrolysis is undisclosed.

The original database lists 445 separate hydrogen production facilities. Since many of these entries miss information on the commissioning date and the installed capacity size, we manually reviewed each entry. We thereby relied on the source provided in the database and on publicly available information from news coverage, industry reports, project websites, and press releases of investors, project developers, and manufacturers. In the course of our review, we could verify information for 186 projects from the original database and amend or adjust entries for 111 projects. We could not verify or complete information for 111 projects due to a lack of publicly accessible information. Furthermore, we excluded 37 projects based on production technologies other than water electrolysis.

In addition, we conducted our own review of hydrogen projects based on industry announcements and media coverage. This review identified 133 additional projects that we added to the data set. Our final data set comprises 430 complete entries, of which 225 represent PtG facilities based on either alkaline, PEM, or SOC technology that were built worldwide between the years 2000–2020. Of these projects, 99 are alkaline electrolysis systems, 112 projects comprise PEM electrolyzers, and 14 facilities are based on SOC technology. If projects had a construction period of more than one year, we use the starting year, that is, the commission date in our calculations. The resulting total cumulative installed capacity across the three PtG technologies amounts to about 200 MW in 2020, which is consistent with recent estimates by industry analysts[9;10].

The IEA recently published an update of the *Hydrogen Projects Database*[11]. This update includes some changes to the list of capacity installations in the previous version from which our review departed. However, the total cumulative installed capacity across the three PtG technologies in 2020 resulting from the update is slightly less than the 200 MW resulting from our database. We attribute this difference to the additional review of capacity installations we conducted.

4 Review of Conversion Efficiency

Information on specific energy consumption stems from the preceding two reviews. In total, we retrieved 229 data points: 130 for alkaline systems over the years 2000–2020, 78 for PEM systems between 2005–2020, and 21 for SOC systems across 2011–2020. We interpret these values as those obtained at full capacity utilization. Alkaline and PEM electrolyzers attain a near-constant energy consumption beyond a small threshold utilization level[12]. For SOC systems, existing literature provides little evidence for the change in energy consumption as a function of capacity utilization. For all technologies, the energy consumption values include the energy required for the electrolytic conversion process and the operation of auxiliary systems, such as control systems and monitoring equipment. Yet, the values exclude the energy needed for heat management.

In analogy to system prices, we converted range estimates (if given) to the arithmetic mean of the lowest and highest points in the range. Furthermore, estimates given in units other than kWh/kg were converted based on the lower heating value of hydrogen (120 MJ/kg) and a density of hydrogen of 0.090 kg/Nm^3. We also checked the boundary and operating conditions of the PtG systems to adjust for factors such as gas compression, water purification, transport and storage of feedstock as well as a potential grid connection. All observations of a technology were winsorized at the 5.0% level in combination with a moving time window of 3 years ranging from 1 year before to 1 year after the year in which the estimates are adjusted. Analog to system prices, this winsorization has a small effect on our findings for all technologies.

5 Learning Estimates by Deployment

Supplementary Table 1 provides detailed results for our regression estimations of the constant elasticity learning curve in equation (1) in the main body of the paper. Learning estimates for the energy consumption of SOC electrolysis are not statistically significant due to the limited sample size. Yet, the results are consistent with industry estimates and anecdotal evidence from manufacturers.

Supplementary Table 1. Regression results for equation (1).

	System prices			**Energy Consumption**		
	Alkaline	PEM	SOC	Alkaline	PEM	SOC
β_0	8.1870***	7.9849***	7.8592***	1.6876***	1.7502***	1.3262***
	(0.0952)	(0.0488)	(0.0865)	(0.0267)	(0.0202)	(0.0233)
β_1	−0.2466***	−0.1910***	−0.2641***	−0.0232**	−0.0246***	−0.0228
	(0.0236)	(0.0151)	(0.0582)	(0.0070)	(0.0064)	(0.0162)
2^{β_1}	0.8429	0.8760	0.8327	0.9841	0.9831	0.9843
Adj. R^2	0.5069	0.6719	0.2432	0.0718	0.1507	0.0471
N	106	79	62	132	78	21

System prices are in 2020 $US/kW and cumulative installed capacity is in MW. All values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** $\leq$ 0.001, ** $\leq$ 0.01, * $\leq$ 0.05.

6 The Effect of System Sizes

Earlier work suggests that the system prices of a PtG facility decline at a diminishing rate as the capacity size of the system increases[12–14]. To examine the potential effect of changes in the size of PtG systems on the trajectory of system prices in our data set, let S_i denote the system size in kW of peak power absorption for a particular technology in year i. The functional specification of the extended constant elasticity learning curve in logarithmic form is then given by:

$$\ln(v_i) = \beta_0 + \beta_1 \cdot \ln(Q_i) + \beta_2 \cdot \ln(S_i) + \mu_i, \tag{A1}$$

where β_2 denotes the size elasticity and μ_i the idiosyncratic error term with $E[\mu_i|Q_i, S_i] = 0$ $\forall i$. As such, the system prices of a PtG technology is estimated to decline with every doubling of system sizes to 2^{β_2}% of its previous value.

Our data set on S_i results from our reviews on system prices, energy efficiency, and installed capacity. In total, we gather 125 observations for alkaline system sizes, 114 for

PEM, and 18 for SOC[8;12;15]. However, most of these observations are disconnected from our data on system prices. Specifically, only 13 size observations for alkaline and 8 size observations for PEM electrolyzers are connected to information on system prices.

Supplementary Table 2. Regression results for equation (A1) **(specification 1)**

	System Prices		
	Alkaline	PEM	SOC
β_0	8.0645***	8.0690***	7.5712***
	(0.1274)	(0.2636)	(0.5067)
β_1	-0.2821***	-0.2141***	-0.3072***
	(0.0341)	(0.0256)	(0.0948)
β_2	0.0383	-0.0021	0.0571
	(0.0267)	(0.0460)	(0.0990)
2^{β_1}	0.8224	0.8621	0.8082
2^{β_2}	1.0269	0.9986	1.0404
Adj. R^2	0.5120	0.7363	0.2347
N	106	79	62

System prices are in 2020 $US/kW, cumulative installed capacity is in MW, system sizes are in MW. All values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** ≤ 0.001, ** ≤ 0.01, * ≤ 0.05.

Given the data limitations, we implement three different specifications to investigate the potential impact of changes in system sizes on system prices. First, we estimate equation (A1) for each technology with S_i given as the annual average system size of the technology. The resulting regression estimates are shown in Supplementary Table 2. Differences between our learning estimates, β_1, in Supplementary Tables 1 and 2 are small. In addition, the estimated coefficients for size, β_2, are close to zero and statistically insignificant. For alkaline and SOC, they are even positive. We attribute the results to the set of system prices available to us, which includes in all sample years ranges of price estimates that are likely to originate to some extent from different capacity sizes.

Some of our data sources[12;15] provide ranges for system sizes with corresponding ranges for system prices. In the second specification, we first assume that the largest (smallest) system size in the size range of a data source corresponds to the lowest (highest) system price per kW in the cost range. We then interpolate the two ranges following the notion that larger systems entail lower system prices per kW. This procedure yields 18 additional pairs of system prices and sizes for alkaline and 11 additional pairs for PEM electrolyzers. We replace the average annual system size with the interpolated values for these pairs and add them to our initial pairs of system prices and sizes. We then estimate (A1) again for all technologies.

Supplementary Table 3. Regression results for equation (A1) **(specification 2)**

	System Prices		
	Alkaline	PEM	SOC
β_0	8.2610***	8.3115***	7.6049***
	(0.1159)	(0.1508)	(0.4153)
β_1	−0.2254***	−0.1977***	−0.3018***
	(0.0303)	(0.0173)	(0.0839)
β_2	−0.0233	−0.0461	0.0510
	(0.0209)	(0.0260)	(0.0814)
2^{β_1}	0.8554	0.8720	0.8113
2^{β_2}	0.9840	0.9685	1.0360
Adj. R^2	0.5081	0.7467	0.2355
N	106	79	62

System prices are in 2020 $US/kW, cumulative installed capacity is in MW, system sizes are in MW. All values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** ≤ 0.001, ** ≤ 0.01, * ≤ 0.05.

Supplementary Table 3 provides the regression results for the second specification. Again, we find no statistically or economically significant parameter estimates for the size coefficient. Meanwhile, the learning estimates for each technology are close to those reported in Figure 1. This finding is consistent with analog studies examining the cost dynamics of other clean energy technologies.

Finally, we compare a specification in which we use only the direct matches and interpolated data, which is intended to produce significant size estimators. Consequently, we exclude all data points with matched yearly average system sizes and remain with our original and interpolated pairs only. We employ this specification to assess the impact of a theoretically significant size estimator on our learning parameters. Due to no available data for SOC, we can only carry out this analysis for alkaline and PEM. We find that alkaline electrolyzers exhibit a $2^{\beta_1} = 84.5\%$ learning curve from cumulative installed capacity and a reduction of $1 - 2^{\beta_2} = 5.5\%$ with every doubling of system sizes (Supplementary Table 4). PEM electrolyzers, in contrast, show an 83.2% learning curve from cumulative installed capacity and a reduction of 7.4% from system sizes. The learning curves for both alkaline and PEM technology are close to those reported in Figure 1, even though the regressions are based on a much smaller data set.

Supplementary Table 4. Regression results for equation (A1) **(specification 3)**

	System Prices		
	Alkaline	PEM	SOC
β_0	8.8281***	8.8914***	-
	(0.2369)	(0.2499)	-
β_1	-0.2451***	-0.2644***	-
	(0.0544)	(0.0398)	-
β_2	-0.0809**	-0.1106*	-
	(0.0247)	(0.0336)	-
2^{β_1}	0.8438	0.8325	-
2^{β_2}	0.9455	0.9262	-
Adj. R^2	0.5760	0.7207	-
N	32	19	-

System prices are in 2020 $US/kW, cumulative installed capacity is in MW, system sizes are in MW. All values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** $\leq$ 0.001, ** $\leq$ 0.01, * $\leq$ 0.05.

7 Learning Curves for the Years 2010–2020

Here we repeat the learning curve estimations for alkaline and PEM electrolyzers covering only the years 2010–2020 to examine the most recent development. The reduction in system prices for alkaline electrolyzers corresponds to a learning curve of $2^{\beta_1} = 82.30\%$ with a 95%-confidence interval of 6.7% ($p < 0.0001$, adj. $R^2 = 0.17$). Accordingly, system prices declined by 17.7% with every doubling of cumulative installed capacity, which is about 2.0% higher than the estimate reported in Figure 1 in the main body. Regarding the conversion efficiency of alkaline systems, the shorter period results in a learning curve of $96.9 \pm 2.33\%$ ($p < 0.05$, adj. $R^2 = 0.05$), which is also lower than in our main specification. Thus, alkaline system improvements appear to originate mainly from the past ten years.

For PEM electrolyzers, the learning curve estimates for system prices and conversion efficiency over the years 2010–2020 are almost identical to those reported in Figure 1 in the main body. In particular, our calculations return a learning curve of $86.3 \pm 2.91\%$ ($p < 0.0001$, adj. $R^2 = 0.50$) for system prices and a learning curve of $98.4 \pm 1.0\%$ ($p < 0.01$, adj. $R^2 = 0.11$) for conversion efficiency. For all specifications, especially for alkaline, the adj. R^2 values are now lower, while the 95%-confidence intervals are higher because of the decreased sample sizes.

Supplementary Table 5. Regression results for last 10 years.

	System prices		**Energy Consumption**	
	Alkaline	PEM	Alkaline	PEM
β_0	8.3304***	8.0475**	1.7747***	1.7452***
	(0.2631)	(0.0769)	(0.0723)	(0.0236)
β_1	−0.2810***	−0.2133**	0.0177*	0.0074**
	(0.0621)	(0.0248)	(0.0177)	(0.0074)
2^{β_1}	0.8230	0.8626	0.9693	0.9841
Adj. R^2	0.1732	0.5029	0.0493	0.1054
N	94	73	106	75

System prices are in 2020 \$US/kW, cumulative installed capacity is in MW. Entries in parentheses are standard errors. Key to statistical significance: *** $\leq$ 0.001, ** $\leq$ 0.01, * $\leq$ 0.05.

8 The Effect of Precious Metal Prices

Some components of PEM electrolyzer systems, such as the electrodes, bipolar plates, and porous transportation layers, so far require the precious metals platinum and iridium[9;16]. To examine the potential effect of a change in the market prices of either metal, let $Platinum_i$ and $Iridium_i$ denote the respective global annual average market prices in year i and β_3 and β_4 the corresponding regression coefficients. The logarithmic form of the extended learning curve is then given by:

$$\ln(v_i) = \beta_0 + \beta_1 \cdot \ln(Q_i) + \beta_3 \cdot Platinum_i + \beta_4 \cdot Iridium_i + \mu_i, \tag{A2}$$

where μ_i is again assumed to have a zero mean and to be uncorrelated with the independent variables.

Market prices for both metals are taken from `www.platinum.matthey.com`. Supplementary Table 6 provides detailed regression results. Similar to before, we find that the differences between our learning estimates, β_1, in Supplementary Tables 1 and 6 are relatively small. At the same time, the estimated coefficients for both metals are economically insignificant.

Supplementary Table 6. Regression results for equation (A2).

	System prices
β_0	8.2219^{***}
	(0.2333)
β_1	-0.1957^{***}
	(0.0210)
β_3	0.0000
	(0.0002)
β_4	-0.0002
	(0.0001)
2^{β_1}	0.8731
Adj. R^2	0.7390
N	79

System prices are in 2020 \$US/kW, cumulative installed capacity is in MW, platinum and iridium prices are in 2020 \$US/ounce. Entries in parentheses are standard errors. Key to statistical significance: $^{***} \leq 0.001$, $^{**} \leq 0.01$, $^{*} \leq 0.05$.

9 Learning Estimates by Time

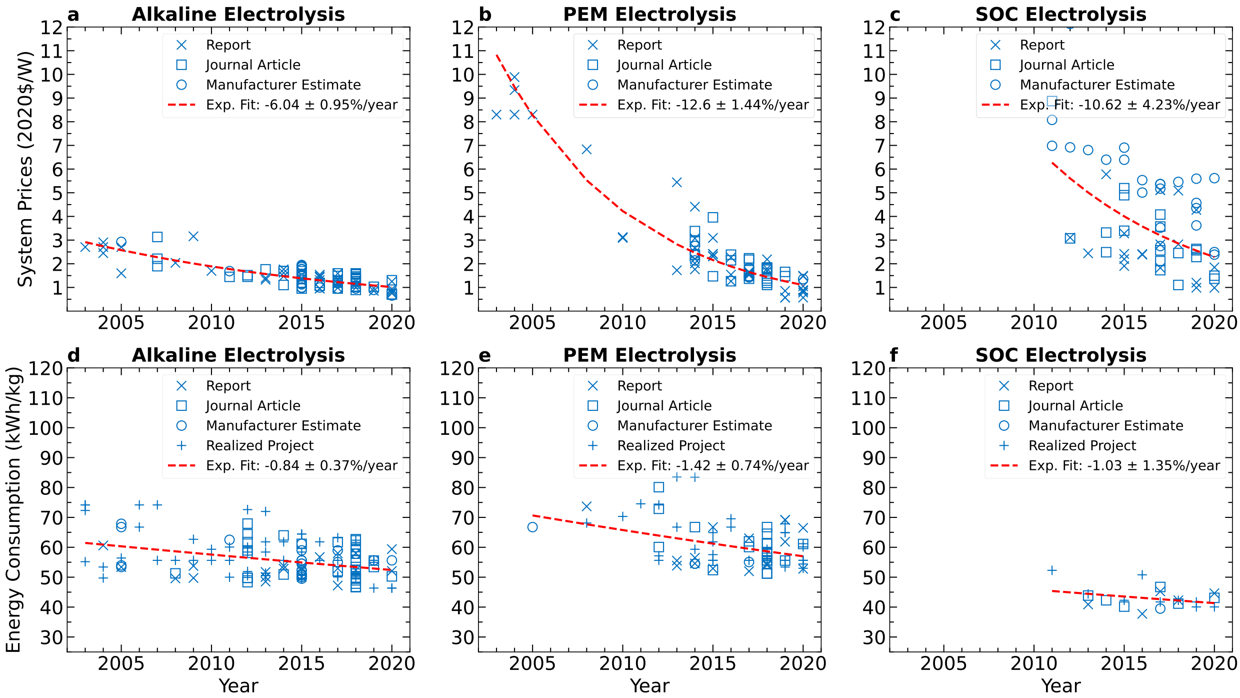
A common alternative to learning curves based on cumulative installed capacity is the estimation of technological progress as a function of time. To that end, we now estimate the development of system prices by means of a univariate regression for a constant elasticity model of the form:

$$\ln(v_i) = \lambda_0 + \lambda_1 \cdot i + \epsilon_i, \tag{A3}$$

where ϵ_i denotes the idiosyncratic error term with $E[\epsilon_i] = 0 \ \forall i$. Accordingly, the system prices of a PtG technology are predicted to fall every year to e^{λ_1} of its value in the preceding year. Our estimation of the changes in a technology's energy consumption is again symmetric.

Supplementary Figure 2a–c shows the system prices of the three electrolysis technologies and our estimates of the corresponding annual price decline. For alkaline electrolyzers, the reduction in system prices across the years 2003–2020 corresponds to an annual decline of $1 - e^{\lambda_1} = 6.0\%$ with a 95%-confidence interval of 1.0% ($p < 0.0001$, adj. $R^2 = 0.56$). In contrast, SOC electrolyzers exhibit a price decline between 2011–2020 described by an annual reduction of $10.6 \pm 4.2\%$ ($p < 0.0001$, adj. $R^2 = 0.25$). PEM electrolyzers show a similarly rapid decline in system prices across 2003–2020 of $12.6 \pm 1.4\%$ ($p < 0.0001$, adj. $R^2 = 0.77$). See Supplementary Table 7 for details.

Supplementary Figure 2d–f shows the changes in energy consumption and our estimates



Supplementary Figure 2. Dynamics of system prices and efficiency over time. This figure shows the trajectory of system prices in 2020 $US and our estimates of the corresponding annual price decline for (**a**) alkaline, (**b**) PEM, and (**c**) SOC electrolyzers. It also shows the development of the energy consumption and our estimate of the corresponding annual improvement for (**d**) alkaline, (**e**) PEM, and (**f**) SOC electrolyzers.

of the annual improvement. We find that the improvement in energy consumption of alkaline systems across the years 2000–2020 corresponds to an annual increase of $0.8 \pm 0.4\%$ ($p < 0.0001$, adj. $R^2 = 0.11$). In contrast, SOC electrolyzers show an annual improvement between 2011–2020 of $1.0 \pm 1.4\%$ ($p < 0.15$, adj. $R^2 = 0.07$). PEM electrolyzers display an annual increase across 2005–2020 of $1.4 \pm 0.7\%$ ($p < 0.0001$, adj. $R^2 = 0.15$).

Supplementary Table 7. Regression results for equation (A3).

	System Prices			Energy Consumption		
	Alkaline	PEM	SOC	Alkaline	PEM	SOC
λ_0	132.7101***	279.1588***	234.6324***	17.9059***	30.5509***	22.2568***
	(10.3038)	(16.8381)	(48.9072)	(3.9154)	(7.6656)	(13.1918)
λ_1	−0.0623***	−0.1347***	−0.1123***	−0.0081***	−0.0143***	−0.0104***
	(0.0051)	(0.0084)	(0.0243)	(0.0019)	(0.0038)	(0.0065)
e^{λ_1}	0.9396	0.8740	0.8740	0.9916	0.9858	0.9897
Adj. R^2	0.5839	0.7686	0.2511	0.1139	0.1461	0.0703
N	106	79	62	132	78	21

System prices are in 2020 $US/kW and time is given in years. Price values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** $\leq$ 0.001, ** $\leq$ 0.01, * $\leq$ 0.05.

10 Future Cumulative Installed Capacity

Our projections consider three alternative scenarios for the growth of cumulative installed electrolysis capacity over the coming decade. The first scenario (called "Past Growth") assumes that the cumulative capacity of each considered technology continues to grow over the coming decade at the same average rate as in the past. As described in the main body of the paper, we estimate the past average growth rate of cumulative capacity for each technology based on a univariate regression for a constant elasticity model of the form:

$$\ln(Q_i) = \lambda_0 + \lambda_1 \cdot i + \epsilon_i, \tag{A4}$$

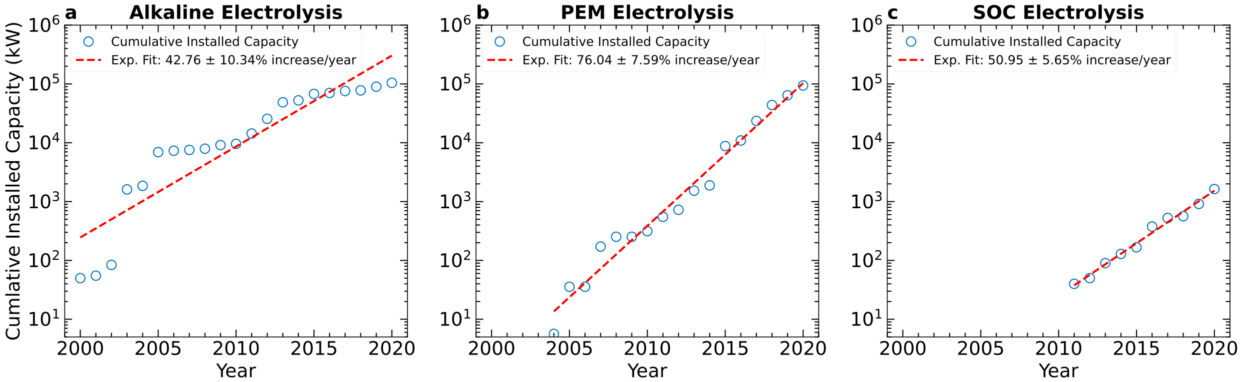
where ϵ_i denotes the idiosyncratic error term with $E[\epsilon_i] = 0 \; \forall i$. Accordingly, the cumulative installed capacity of a PtG technology is predicted to increase every year to e^{λ_1} of its value in the preceding year. The detailed regression results are provided in Supplementary Table 8, while an illustration is provided in Supplementary Figure 3.

The second scenario (called "Policy Target") assumes that cumulative installed electrolysis capacity will grow such that global installed capacity in the year 2030 meets an aggregate of policy targets. At the point of our analysis, the aggregate target amounts to about 115 GW and stems from the following national and supranational hydrogen strategies: Chile 25 GW[17] and the European Union with 40 GW in Europe and 40 GW in its neighborhood, in particular North Africa[18], where 36 GW are currently targeted to be built in France (6.5 GW), Germany (5.0 GW), Italy (5.0 GW), Scotland (5.0 GW), Spain (4.0 GW), the Netherlands (3.5 GW), Portugal (2.25 GW), Poland (2 GW), Austria (1.5 GW), and Denmark (1.3 GW)[19–29].

Supplementary Table 8. Regression results for equation (A4).

	Alkaline	**PEM**	**SOC**
λ_0	-713.3481^{***}	-1137.7098^{***}	-831.4175^{***}
	(72.1765)	(41.8446)	(33.3476)
λ_1	0.3560^{***}	0.5655^{***}	0.4118^{***}
	(0.0359)	(0.0208)	(0.0165)
$e^{\lambda_1} - 1$	0.4276	0.7604	0.5095
Adj. R^2	0.8295	0.9775	0.9857
N	21	18	10

Cumulative installed capacity is in MW. Entries in parentheses are standard errors. Key to statistical significance: $^{***} \leq 0.001$, $^{**} \leq 0.01$, $^{*} \leq 0.05$.



Supplementary Figure 3. Past development of cumulative installed capacity. This figure shows the growth in cumulative installed capacity for (**a**) alkaline, (**b**) PEM, and (**c**) SOC electrolyzers. It also shows our estimates of the corresponding annual growth rates.

Since the policy targets are technology-agnostic and specified for installed rather than cumulative installed capacity, we implement two adjustments. First, we assume that a technology's share of the total cumulative installed capacity in 2030 is equal to the share the technology obtains in the Past-Growth scenario for 2030. Given the observed cumulative capacity for each electrolysis technology in 2020 and our estimate of installed capacity in 2030, we then interpolate the exponential growth in capacity installation required for the years 2021–2029. In addition, we account for potential capacity depletion by adding for each year from 2021–2030 the amount of installed capacity that is expected to have gone offline until that year based on the installation year and the useful lifetime assumed in our calculations. Yet, these additions are small relative to the growth required to reach the overall target in 2030.

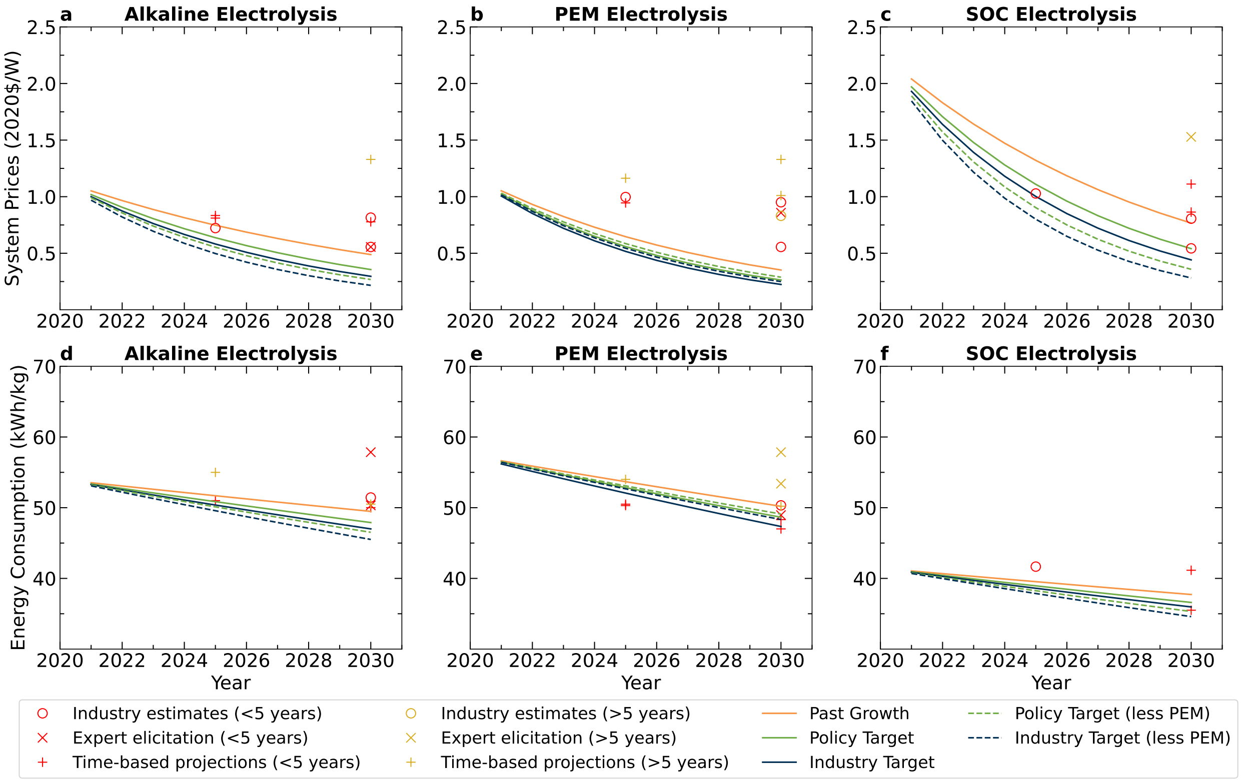
Our third scenario (called "Industry Target") is directly analogous to the second scenario

Supplementary Table 9. Estimates of cumulative installed capacity by 2030.

in %	**Alkaline**	**PEM**	**SOC**	**Total**
Past Growth	3,670	26,898	100	30,688
Policy Target	13,772	100,861	376	115,009
Policy Target (less PEM)	45,002	68,221	1,787	115,009
Industry Target	29,682	217,458	812	247,952
Industry Target (less PEM)	110,143	133,362	4,446	247,952

with the exception that the aggregate target in 2030 stems from announcements by project developers, hydrogen customers, and hydrogen industry associations. The aggregate target currently amounts to about 248 GW of capacity that is planned to be installed by 2030 in the following countries: China 100 GW, Spain 72 GW, Australia 27 GW, the Netherlands 8 GW, Oman 6.7 GW, Germany 6.5 GW, Greece 5.0 GW, Denmark 3.6 GW, Brazil 3.4 GW, Chile 3.0 GW, the United Kingdom 2.1 GW, Ireland, 1.6 GW, Romania 1.6 GW, Sweden 1.5 GW, Belgium 1.2 GW, France 1.2 GW, Portugal 1.1 GW, Norway 1.0 GW, Italy 0.8 GW, Poland 0.3 GW, Bulgaria 0.2 GW, and other countries in the European Union 0.4 GW[30–33]. In case targets for installed capacity in 2030 were given in a range, we converted these to the arithmetic mean of the lowest and highest targets in the range. All included announcements for installed capacity have a scheduled completion date before 2030.

Some industry observers argue that the growth in PEM installations over the coming years might be slower than in the past because of shortages of rare earth materials and bans on fluoric coatings, which are expected in some jurisdictions, including the European Union. To examine this possibility, we analyze variants of the Policy and Industry Target scenarios. Here, we assume that each technology will obtain the same cumulative installed capacity in 2030 as in the Past-Growth scenario. The remaining growth in capacity required to reach the policy (or industry) target is then equally distributed between alkaline and PEM electrolysis, where each one obtains a share of 49%. SOC technology is assumed to obtain the remaining share of 2%, representing the relative youth of the technology. The resulting estimates for the alternative scenarios in cumulative installed capacity are provided in Supplementary Table 9. The corresponding projections for the trajectories of system prices and conversion efficiency are provided in Supplementary Figure 4.



Supplementary Figure 4. Prospects for system prices and efficiency (all scenarios). This figure shows our projections of the potential development of system prices in 2020 $US for (**a**) alkaline, (**b**) PEM, and (**c**) SOC electrolyzers. It also shows our projections of the potential trajectory of energy consumption for (**d**) alkaline, (**e**) PEM, and (**f**) SOC electrolyzers.

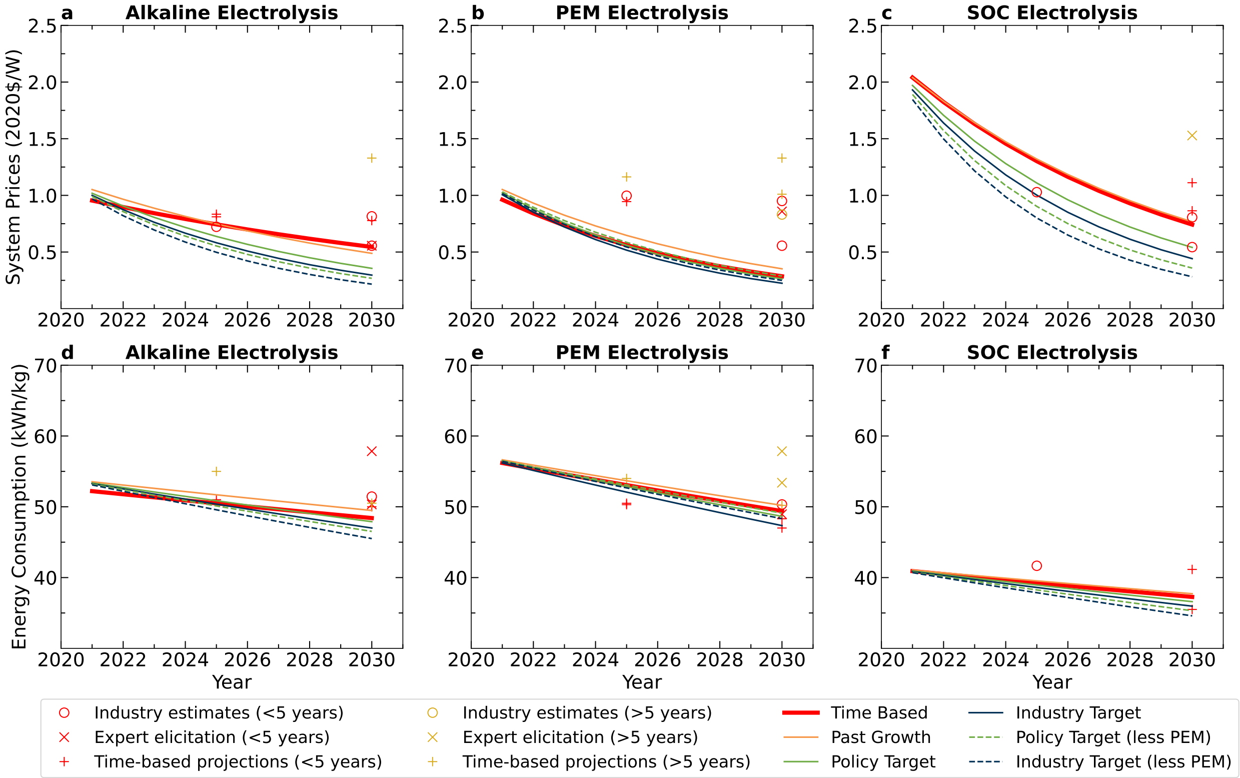
11 Future Performance by Time

We now use our estimates in Supplementary Figure 2 to project an alternative trajectory of future system prices and energy consumption for each PtG technology. As one would expect, the resulting trajectories for system prices and energy consumption shown in Supplementary Figure 5 are close, if not identical, to the previous trajectories corresponding to the Past-Growth scenario. As an exception to this, the time-based projection for system prices of PEM electrolyzers is closer to the trajectory of the Industry-Target scenarios. We attribute this discrepancy to a large share of lower price observations in recent years.

For further robustness, we also examine a specification based on time and cumulative installed capacity. The bivariate constant elasticity functional form is given by:

$$\ln(v_i) = \beta_0 + \beta_1 \cdot \ln(Q_i) + \beta_2 \cdot i + \epsilon_i, \tag{A5}$$

where ϵ_i denotes the idiosyncratic error term with $E[\epsilon_i|Q_i] = 0 \ \forall i$. The estimation of the changes in a technology's energy consumption is again symmetric.



Supplementary Figure 5. Prospects for system prices and efficiency based on time. This figure shows our time-based projections of the potential development of system prices in 2020 \$US for (**a**) alkaline, (**b**) PEM, and (**c**) SOC electrolyzers. It also shows our time-based projections of the potential trajectory of energy consumption for (**d**) alkaline, (**e**) PEM, and (**f**) SOC electrolyzers.

Supplementary Table 10 provides detailed regression results. For both system prices and energy consumption, the regression coefficients for cumulative installed capacity are now positive and statistically insignificant, while the coefficients for time are close to those reported in Supplementary Table 7. These results can be attributed to severe multicollinearity between the two independent variables. Specifically, alkaline electrolyzers exhibit a Pearson correlation coefficient of 0.95 and a variance inflation factor of 10.3. PEM systems show a Pearson correlation coefficient of 0.99 and a variance inflation factor of 52.0. Finally, SOC technology shows a Pearson correlation coefficient of 0.99 and a variance inflation factor of 58.1. Nevertheless, projected trajectories for system prices and energy consumption based on the regression estimates are close to the time-based projections reported in Supplementary

Figure 5. As such, all scenarios and specifications in our calculations yield a consistent assessment of the magnitudes and trends in price and efficiency improvements.

Supplementary Table 10. Regression results for equation (A5)

	System Prices			**Energy Consumption**		
	Alkaline	PEM	SOC	Alkaline	PEM	SOC
β_0	153.6344***	405.2188**	313.6040	29.9637***	2.7511	128.1963
	(32.8751)	(121.1544)	(376.1014)	(10.1289)	(44.1837)	(98.7539)
β_1	0.0468	−0.1974	0.0942	0.0219	−0.0238	0.1295
	(0.0698)	(0.0602)	(0.4445)	(0.0180)	(0.0372)	(0.1196)
β_2	−0.0727***	0.1029**	−0.1514	−0.0141**	−0.0005	−0.0628
	(0.0164)	(0.0979)	(0.1863)	(0.0051)	(0.0220)	(0.0489)
2^{β_1}	1.0330	0.8721	1.0674	1.0153	0.9837	1.0939
e^{β_2}	0.9298	1.0739	0.8595	0.9860	0.9995	0.9391
Adj. R^2	0.5817	0.7689	0.2389	0.1275	0.1394	0.0786
N	106	79	62	132	78	21

System prices are in 2020 $US/kW, cumulative installed capacity is in MW, average system sizes are in MW. All values are logarithmized using the natural logarithm (ln). Entries in parentheses are standard errors. Key to statistical significance: *** ≤ 0.001, ** ≤ 0.01, * ≤ 0.05.

12 Levelized Cost of Hydrogen

Supplementary Table 11 provides detailed inputs and outputs for our LCOH calculations.

Supplementary Table 11. Estimates of levelized cost of hydrogen by 2030.

in 2020 $US	**Source**	**Alkaline**	**PEM**	**SOC**
General parameters				
Economic lifetime, T (years)	[1]	20	20	20
Cost of capital, r (%)	[2]	5.00	5.00	5.00
Number of hours per year, m (h)		8,760	8,760	8,760
Corporate income tax rate, α (%)	[3]	21.00	21.00	21.00
Depreciation method (–)*	[4]	3	3	3
Degradation rate, x (%)	[7]	1.00	1.00	1.60
Electricity buying price, $q_i(t)$ ($/kWh)	[5]	0.0359	0.0359	0.0359
Past Growth				
System price, v ($/kW)	[6]	475	352	767
Fixed operating cost, F_i ($/kW)	[6]	9	9	15
Hydrogen conversion rate, η^{-1} (kWh/kg)	[6]	49.48	49.84	42.72
Average optimized capacity factor, CF^* (%)		0.73	0.66	0.85
Levelized cost of hydrogen, $LCOH$ ($/kg)		1.89	1.81	1.91
Policy Target				
System price, v ($/kW)	[6]	340	263	536
Fixed operating cost, F_i ($/kW)	[6]	7	7	11
Hydrogen conversion rate, η^{-1} (kWh/kg)	[6]	47.86	48.21	41.58
Average optimized capacity factor, CF^* (%)		0.60	0.53	0.74
Levelized cost of hydrogen, $LCOH$ ($/kg)		1.71	1.66	1.69
Industry Target				
System price, v ($/kW)	[6]	284	225	441
Fixed operating cost, F_i ($/kW)	[6]	6	6	9
Hydrogen conversion rate, η^{-1} (kWh/kg)	[6]	46.51	48.72	40.96
Average optimized capacity factor, CF^* (%)		0.52	0.46	0.68
Levelized cost of hydrogen, $LCOH$ ($/kg)		1.63	1.59	1.59

*3: 20-year 150%-declining balance; Sources: [1],[34] [2],[35;36] [3],[37] [4],[38] [5], `www.ercot.com`,[39] [6], own analysis [7],[3;12;40].

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