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Economics of converting renewable power to hydrogen

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Supplementary Information:
Economics of Converting Renewable Power to Hydrogen

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Supplementary Table 1. List of Symbols and Acronyms.

α	Corporate income tax rate	L	Levelization factor
AEL	Alkaline electrolysis	LCOE	Levelized cost of electriciy
β	Adjustment rate of electricity price	LFCH	Levelized fixed cost of hydrogen
c	Cost of capacity	m	Number of hours per year
$CF(t)$	Capacity factor at time t	$\mu(t)$	Deviation factor of prices
CFL_i^0	Pre-tax cash flow in year i	NPV	Net present value
CFL_i	After-tax cash flow in year i	$p_e(t)$	Electricity price at time t
$CM(t)$	Contribution magin at time t	p_h	Hydrogen price
$CP_h(t)$	Conversion premium at time t	PP	Production premium
CV_h	Conversion value of hydrogen	PEM	Polymer electrolyte membrane
Δ	Tax factor	PTC	Production tax credit
$\delta(t)$	Deviation factor of price premium	ptc	Levelized production tax credit
d_i	Tax depreciation in year i	PtG	Power-to-Gas
$D(i)$	LCOE minus adj. market price in year i	r	Cost of capital
$\epsilon(t)$	Deviation factor of generation	SOEC	Solid Oxide Electrolyzer Cell
η	Conversion rate of Power-to-Gas	SP	System price of capacity
f	Fixed operating cost	T	Life of capacity investment
F_i	Fixed operating cost in year i	w	Variable operating cost
γ	Discount factor	WACC	Weighted average cost of capital
Γ	Co-variation coefficient	w	Variable operating cost
I_i	Taxable income in year i	W_i	Variable operating cost in year i
k	Size of capacity investment	x^{i-1}	Degradation factor in year i
kg	Kilogram	z	Conversion of renewable energy
kW	Kilowatt	$z(t)$	Conversion capacity at time t
kWh	Kilowatt hour		

Supplementary Note 1

Proof of the NPV Expression

The NPV of a hybrid energy system of capacity sizes $(k_e = 1, k_h)$ is given by the present value of future operating cash flows less the initial capacity investment:

$$NPV(k_e, k_h) = \sum_{i=1}^{T} CFL_i(k_e = 1, k_h) \cdot \gamma^i - (k_e \cdot SP_e + k_h \cdot SP_h), \tag{A1}$$

with $CFL_i(k_e, k_h)$ as the after-tax operating cash flow in year i. It is given by the difference between the pre-tax cash flow in year i, $CFL_i^o(k_e, k_h)$, and current corporate income taxes, given by the tax rate, α, applied to the taxable income, $I_i(k_e, k_h)$:

$$CFL_i(k_e, k_h) = CFL_i^o(k_e, k_h) - \alpha \cdot I_i(k_e, k_h). \tag{A2}$$

The pre-tax operating cash flow in year i comprises the optimized contribution margin of a hybrid energy system less the fixed operating costs:

$$CFL_i^o(k_e,k_h) = x^{i-1}\int\limits_0^m CM(t|k_e,k_h)dt - (k_e \cdot F_{ei} + k_h \cdot F_{hi}), \tag{A3}$$

with $x < 1$ denoting the degradation factor, that is, the percentage by which capacity declines in each subsequent year. The firm's taxable income in year i is then given by the pre-tax cash flow less depreciation, with d_i denoting the allowable depreciation percentage in year i.

$$I_i(k_e,k_h) = CFL_i^o(k_e,k_h) - (k_e \cdot SP_e + k_h \cdot SP_h) \cdot d_i. \tag{A4}$$

Combining the expressions in (A2), (A3), and (A4), the net present value can be restated as:

$$\begin{aligned} NPV(k_e,k_h) =& (1-\alpha) \cdot \left[\sum_{i=1}^{T} \gamma^i \cdot \left(x^{i-1}\int\limits_0^m CM(t|k_e,k_h)dt - (k_e \cdot F_{ei} + k_h \cdot F_{hi})\right)\right] \\ & - (1 - \alpha \sum_{i=1}^{T} d_i \cdot \gamma^i) \cdot (k_e \cdot SP_e + k_h \cdot SP_h). \end{aligned} \tag{A5}$$

Since the tax factor was defined as:

$$\Delta = \frac{1 - \alpha \cdot \sum\limits_{i=1}^{T} d_i \cdot \gamma^i}{1-\alpha}, \tag{A6}$$

the expression for the NPV reduces to:

$$\begin{aligned} NPV(k_e,k_h) =& (1-\alpha) \cdot \left[\sum_{i=1}^{T} \gamma^i \cdot \left(x^{i-1}\int\limits_0^m CM(t|k_e,k_h)dt - (k_e \cdot F_{ei} + k_h \cdot F_{hi})\right)\right. \\ & \left. - \Delta(k_e \cdot SP_e + k_h \cdot SP_h)\right]. \end{aligned} \tag{A7}$$

It will be convenient to pull out the *levelization factor* $L \equiv m \cdot \sum\limits_{i=1}^{T} x^{i-1} \cdot \gamma^i$:

$$\begin{aligned} NPV(k_e,k_h) =& (1-\alpha) \cdot L \cdot \left[\frac{1}{m}\int\limits_0^m CM(t|k_e,k_h)dt - \frac{k_e \cdot F_{ei} + k_h \cdot F_{hi}}{m \cdot \sum\limits_{i=1}^{T} x^{i-1} \cdot \gamma^i}\right. \\ & \left. - \Delta \cdot \frac{k_e \cdot SP_e + k_h \cdot SP_h}{m \cdot \sum\limits_{i=1}^{T} x^{i-1} \cdot \gamma^i}\right]. \end{aligned} \tag{A8}$$

The body of the paper and *Methods* introduced the levelized cost of electricity of the renewable energy source as $LCOE = f_e + \Delta \cdot c_e$ (assuming a zero variable cost for generating renewable electricity), and $LFCH = f_h + \Delta \cdot c_h$. Here, f_e and f_h refer to the time averaged operating fixed costs and c_e and c_h to the unit costs of capacity of the two subsystems. We thus obtain:

$$NPV(k_e, k_h) = (1-\alpha) \cdot L \cdot \left[\frac{1}{m}\int\limits_0^m CM(t|k_e, k_h)dt - CF \cdot k_e \cdot LCOE - k_h \cdot LFCH\right]. \tag{A9}$$

We next substitute the optimized contribution margin into the expression for the NPV:

$$\begin{aligned} NPV(k_e, k_h) =& (1-\alpha) \cdot L \cdot \left[\frac{1}{m}\left(k_e \int\limits_0^m p_e(t) \cdot CF(t)dt + \int\limits_0^m CP_h(t) \cdot z(t|k_e, k_h)dt\right)\right. \\ & \left. - CF \cdot k_e \cdot LCOE - k_h \cdot LFCH\right]. \end{aligned} \tag{A10}$$

The final step accounts for the temporal co-variations in prices and capacity factors[1]. We denote by $\epsilon(t)$ and and $\mu(t)$ the multiplicative deviation factors that reconcile of $CF(t)$ and $p_e(t)$ with their annual average values CF and p_e, respectively. Thus:

$$\epsilon(t) = \frac{CF(t)}{CF} \text{ and } \mu(t) = \frac{p_e(t)}{p_e}. \tag{A11}$$

The average capacity factor is given by $CF = \frac{1}{m}\int\limits_0^m CF(t)dt$ and the average electricity price is given by $p_e = \frac{1}{m}\int\limits_0^m p_e(t)dt$. The covariation between the output and the price can then be summarized by the co-variation coefficient:

$$\Gamma = \frac{1}{m}\int\limits_0^m \epsilon(t) \cdot \mu(t)\, dt. \tag{A12}$$

We further recall that, by definition, $\delta(t) \cdot CP_h = CP_h(t)$ and

$$z(k_e, k_h) \equiv \frac{1}{m}\int\limits_0^m z(t|k_e, k_h) \cdot \delta(t)\, dt.$$

Taken together, the expression for the NPV simplifies to:

$$NPV(k_e, k_h) = (1-\alpha) \cdot L \cdot [(\Gamma \cdot p_e - LCOE) \cdot CF \cdot k_e + CP_h \cdot z(k_e, k_h) - LFCH \cdot k_h]. \tag{A13}$$

■

Proof of Finding 1

For sufficiency, we show that given $k_e = 1$ the partial derivative:

$$\left.\frac{\partial}{\partial k_h} NPV(k_e = 1, k_h)\right|_{k_h=0} > 0, \tag{A14}$$

if the inequality in the statement of Finding 1 holds.

$$\left.\frac{\partial}{\partial k_h} NPV(1, k_h)\right|_{k_h=0} = CP_h \cdot \frac{\partial}{\partial k_h} z(1, 0) - LFCH \tag{A15}$$

$$= CP_h - LFCH > 0. \tag{A16}$$

For necessity, suppose the condition in the statement of Finding 1 ($CP_h - LFCH$) is not met, yet the hybrid energy system is economically viable and thus $NPV(1, k_h) \geq NPV(1, 0)$ for some k_h. We then obtain:

$$NPV(1, k_h) - NPV(1, 0) = \int_0^{k_h} \frac{\partial}{\partial k_h} NPV(1, u) du \tag{A17}$$

$$= \int_0^{k_h} \left[CP_h \cdot \frac{\partial}{\partial k_h} z(1, u) - LFCH\right] du \tag{A18}$$

$$\leq \int_0^{k_h} [CP_h - LFCH] \, du \tag{A19}$$

$$= k_h \cdot [CP_h - LFCH] \tag{A20}$$

$$< 0, \tag{A21}$$

a contradiction. ■

Proof of Finding 2

Suppose the hybrid energy system is economically viable, that is, $NPV(1, k_h^*(1)) > 0$. Finding 1 established that $k_h^*(1) > 0$ if only if $CP_h - LFCH > 0$. Now suppose that, contrary to the claim, $CP_h - LFCH + (\Gamma \cdot p_e - LCOE) \cdot CF < 0$. It would then follow that:

$$NPV(1, k_h^*(1)) = (1 - \alpha) \cdot L \cdot [CP_h \cdot z(1, k_h^*(1)) - LFCH \cdot k_h^*(1) + (\Gamma \cdot p_e - LCOE) \cdot CF] \tag{A22}$$

$$\leq (1 - \alpha) \cdot L \cdot [CP_h \cdot k_h^*(1) - LFCH \cdot k_h^*(1) + (\Gamma \cdot p_e - LCOE) \cdot CF] \tag{A23}$$

$$\leq (1 - \alpha) \cdot L \cdot [CP_h - LFCH + (\Gamma \cdot p_e - LCOE) \cdot CF] \tag{A24}$$

$$< 0. \tag{A25}$$

The first inequality follows from the observation that, by definition, $z(1, k_h^*(1)) \leq k_h^*(1)$, while the second inequality relies on $k_h^*(1) \leq 1$ due to the fact that $\lim_{k_h \to 1} \frac{\partial}{\partial k_h} z(1, k_h) = 0$. ■

Supplementary Table 2. Valuation parameters.

	Germany	Texas	Source
General			
Economic lifetime, T	30 years	30 years	[2]
Corporate income tax rate, α	35.00 %	35.00 %	German and U.S. Tax Code
Degradation rate, x_i	0.80 %	0.80 %	[3;4]
Depreciation rate, d_i	6.25 % (16y linear)	5y MACRS	[5;6]
Cost of capital (WACC), r	4.00 %	6.00 %	[7;8]
Number of hours per year, m	8,760	8,760	
Subsidy lifetime	20 years	10 years	[9;10]
Wind energy			
Capacity factor, CF	30.27 %	34.61 %	Own data and[11;12]
Variable operating cost, w_e	0.00 €/kWh	0.00 \$/kWh	[12]
Fixed operating cost, F_e	38.00 €/kW	17.00 \$/kW	[11;12]
Acquisition cost, SP_e	1,367 €/kW	1,596 \$/kW	[3;12]
Power-to-Gas			
Conversion rate, η	0.019 kg/kWh	0.019 kg/kWh	[13]
Variable operating cost, w_h	0.10 €/kg	0.08 \$/kg	Estimation of water cost.[*]
Fixed operating cost, F_h	45.00 €/kW	39.50 \$/kW	Own review, see *Methods* of paper
Acquisition cost, SP_h	2,287 €/kW	2,009 \$/kW	Own review, see *Methods* of paper
Prices			
Selling price of wind energy, p_e	3.18 €¢/kWh	2.55 \$¢/kWh	`www.eex.com`; `www.ercot.com`

[*] Conversion to \$ with average exchange rate of 2015 (1.1104 \$/€, see European Central Bank) and U.S. state index (0.7910, [14]).

Supplementary Table 3. Cost structure of Power-to-Gas.

Fundament and access	42.00 €/kW
Power connection	150.00 €/kW
Electrolyzer	1,863.00 €/kW
Piping	4.00 €/kW
Compression	56.00 €/kW
Buffer	52.00 €/kW
Feed-in system	56.00 €/kW
Other	64.00 €/kW
Total	**2,287.00 €/kW**

The cost for the balance of system is based on ref.[15].

Supplementary Table 4. Feed-in Premium in Germany.

	Specification	Value	Unit
Number of years with start premium		5.00	years
Reference output per turbine	100 %	9,649,986	kWh
Valuation basis	130 %	12,544,982	kWh
Average output per wind turbine (2015)		8,086,946	kWh
% of reference output		84.00	%
§49 (2) 1 - additional months	0.36 %	83.33	months
§49 (2) 2 - additional months	0.48 %	33.74	months
Total additional months of start premium		117.08	months
Additional years of start premium		9.76	years
Total number of years with start premium		**14.76**	**years**

The table summarizes the calculation of the Feed-in Premium in Germany. Since we base the calculations on 2015 figures, the Feed-in Premium falls under the Renewable Energy Act from

2014 (Art. 19, 49) for the first two years[16]. The amount of the premium is the difference between a total value that is defined by law and a monthly average market value of wind energy. This total value amounts to 8.95 €¢/kWh for the first five years of operation and 4.95 €¢/kWh for the remaining 15 years. However, this period of higher subsidies may be extended depending on the output of the wind park. The period is extended by one month per 0.36% difference by which the wind yield of the wind facility is below 130% of a reference output and by one month per 0.48% difference below 100% of the reference output. This benchmark is provided by an independent agency and amounts to 48,249,931 kWh for 5 years for the turbine in our study, an Enercon E-101 with 149m hub height[17]. The monthly average market value is the monthly average of the hourly spot prices weighted by the electricity produced in kWh and provided by ref.[18].

Supplementary Table 5. Current Economic Viability of Renewable Hydrogen.

	Germany	**Texas**
Wind energy		
Variable operating cost	0.00 €¢/kWh	0.00 $¢/kWh
Fixed operating cost	1.58 €¢/kWh	0.61 $¢/kWh
Capacity Cost	3.29 €¢/kWh	4.18 $¢/kWh
Tax factor	1.1463	1.0549
Levelized PP or PTC	4.73 €¢/kWh	1.99 $¢/kWh
Levelized cost of electricity	5.36 €¢/kWh	5.02 $¢/kWh
Electricity price	3.18 €¢/kWh	2.55 $¢/kWh
Co-variation coefficient	0.88	0.88
Profit margin of wind energy	0.65 €¢/kWh	-0.27 $¢/kWh
Power-to-Gas		
Fixed operating cost	0.63 €¢/kWh	0.55 $¢/kWh
Capacity Cost	1.67 €¢/kWh	1.82 $¢/kWh
Levelized fixed cost of hydrogen	2.54 €¢/kWh	2.47 $¢/kWh
Hybrid energy system		
Conversion premium of hydrogen	2.85 €¢/kWh	4.23 $¢/kWh
Break-even price of hydrogen	3.23 €/kg	3.53 $/kg
Optimal capacity of PtG	0.01 kW	0.29 kW

As noted in the main text of the paper, the feed-in requirement of the subsidy in Germany reflects a prohibitively large opportunity cost to convert renewable energy to hydrogen. If the requirement was maintained in its current form, the break-even price of hydrogen would increase by 3.21 €/kg and therefore almost double.

Supplementary Table 6. Germany, prospects for $\beta = .975$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.18	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.12	0.01
2018	4.00	30.91	1,209	1,975	3.17	3.07	0.01
2019	4.00	31.12	1,161	1,881	3.16	3.02	0.01
2020	4.00	31.34	1,115	1,791	3.14	2.96	0.01
2021	4.00	31.56	1,070	1,706	3.12	2.91	0.01
2022	4.00	31.78	1,027	1,625	3.09	2.85	0.01
2023	4.00	32.00	986	1,547	3.07	2.80	0.01
2024	4.00	32.23	947	1,473	3.03	2.75	0.01
2025	4.00	32.45	909	1,403	3.00	2.69	0.01
2026	4.00	32.68	872	1,336	2.97	2.64	0.01
2027	4.00	32.91	838	1,272	2.93	2.59	0.01
2028	4.00	33.14	804	1,212	2.89	2.54	0.01
2029	4.00	33.37	772	1,154	2.85	2.49	0.01
2030	4.00	33.61	741	1,099	2.81	2.44	0.01

Supplementary Table 7. Germany, prospects for $\beta = .950$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.18	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.12	0.01
2018	4.00	30.91	1,209	1,975	3.11	3.04	0.01
2019	4.00	31.12	1,161	1,881	3.04	2.96	0.01
2020	4.00	31.34	1,115	1,791	2.97	2.88	0.01
2021	4.00	31.56	1,070	1,706	2.91	2.81	0.01
2022	4.00	31.78	1,027	1,625	2.85	2.73	0.01
2023	4.00	32.00	986	1,547	2.79	2.67	0.01
2024	4.00	32.23	947	1,473	2.74	2.60	0.01
2025	4.00	32.45	909	1,403	2.68	2.54	0.01
2026	4.00	32.68	872	1,336	2.63	2.48	0.01
2027	4.00	32.91	838	1,272	2.58	2.42	0.01
2028	4.00	33.14	804	1,212	2.53	2.36	0.01
2029	4.00	33.37	772	1,154	2.48	2.31	0.01
2030	4.00	33.61	741	1,099	2.43	2.26	0.01

Supplementary Table 8. Germany, prospects for $\beta = .925$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.18	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.12	0.01
2018	4.00	30.91	1,209	1,975	3.04	3.01	0.01
2019	4.00	31.12	1,161	1,881	2.92	2.90	0.01
2020	4.00	31.34	1,115	1,791	2.80	2.79	0.01
2021	4.00	31.56	1,070	1,706	2.69	2.69	0.01
2022	4.00	31.78	1,027	1,625	2.58	2.60	0.01
2023	4.00	32.00	986	1,547	2.48	2.51	0.01
2024	4.00	32.23	947	1,473	2.39	2.42	0.01
2025	4.00	32.45	909	1,403	2.30	2.34	0.01
2026	4.00	32.68	872	1,336	2.21	2.27	0.01
2027	4.00	32.91	838	1,272	2.13	2.19	0.01
2028	4.00	33.14	804	1,212	2.06	2.13	0.01
2029	4.00	33.37	772	1,154	1.99	2.06	0.01
2030	4.00	33.61	741	1,099	1.92	2.00	0.01

Supplementary Table 9. Germany, prospects for $\beta = .950$ and $\xi = 2.50\%$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.17	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.12	0.01
2018	4.00	30.91	1,209	1,975	3.12	3.04	0.01
2019	4.00	31.12	1,161	1,881	3.06	2.96	0.01
2020	4.00	31.34	1,115	1,791	3.01	2.89	0.01
2021	4.00	31.56	1,070	1,706	2.95	2.82	0.01
2022	4.00	31.78	1,027	1,625	2.90	2.75	0.01
2023	4.00	32.00	986	1,547	2.85	2.68	0.01
2024	4.00	32.23	947	1,473	2.81	2.62	0.01
2025	4.00	32.45	909	1,403	2.76	2.55	0.01
2026	4.00	32.68	872	1,336	2.72	2.49	0.01
2027	4.00	32.91	838	1,272	2.68	2.44	0.01
2028	4.00	33.14	804	1,212	2.64	2.38	0.01
2029	4.00	33.37	772	1,154	2.60	2.33	0.01
2030	4.00	33.61	741	1,099	2.56	2.27	0.01

Supplementary Table 10. Germany, prospects for $\beta = .950$ and $\xi = 5.00\%$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.17	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.12	0.01
2018	4.00	30.91	1,209	1,975	3.13	3.04	0.01
2019	4.00	31.12	1,161	1,881	3.08	2.97	0.01
2020	4.00	31.34	1,115	1,791	3.04	2.89	0.01
2021	4.00	31.56	1,070	1,706	3.00	2.82	0.01
2022	4.00	31.78	1,027	1,625	2.96	2.75	0.01
2023	4.00	32.00	986	1,547	2.93	2.68	0.01
2024	4.00	32.23	947	1,473	2.89	2.62	0.01
2025	4.00	32.45	909	1,403	2.86	2.55	0.01
2026	4.00	32.68	872	1,336	2.83	2.48	0.01
2027	4.00	32.91	838	1,272	2.80	2.42	0.01
2028	4.00	33.14	804	1,212	2.76	2.35	0.01
2029	4.00	33.37	772	1,154	2.73	2.29	0.01
2030	4.00	33.61	741	1,099	2.70	2.22	0.01

Supplementary Table 11. Germany, prospects for $\beta = .950$ and $\xi = 7.50\%$.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.23	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.17	0.01
2017	4.00	30.69	1,260	2,074	3.18	3.11	0.01
2018	4.00	30.91	1,209	1,975	3.14	3.04	0.01
2019	4.00	31.12	1,161	1,881	3.11	2.97	0.01
2020	4.00	31.34	1,115	1,791	3.08	2.89	0.01
2021	4.00	31.56	1,070	1,706	3.05	2.82	0.01
2022	4.00	31.78	1,027	1,625	3.03	2.74	0.01
2023	4.00	32.00	986	1,547	3.01	2.67	0.01
2024	4.00	32.23	947	1,473	2.98	2.59	0.01
2025	4.00	32.45	909	1,403	2.95	2.51	0.01
2026	4.00	32.68	872	1,336	2.92	2.43	0.01
2027	4.00	32.91	838	1,272	2.90	2.34	0.01
2028	4.00	33.14	804	1,212	2.88	2.26	0.01
2029	4.00	33.37	772	1,154	2.85	2.18	0.01
2030	4.00	33.61	741	1,099	2.83	2.10	0.01

Supplementary Table 12. Germany, prospects for $\beta = .950$ and 10% rebate.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	3.08	0.01
2016	4.00	30.48	1,312	2,178	3.18	3.03	0.01
2017	4.00	30.69	1,260	2,074	3.18	2.98	0.01
2018	4.00	30.91	1,209	1,975	3.11	2.91	0.01
2019	4.00	31.12	1,161	1,881	3.04	2.83	0.01
2020	4.00	31.34	1,115	1,791	2.97	2.76	0.01
2021	4.00	31.56	1,070	1,706	2.91	2.69	0.01
2022	4.00	31.78	1,027	1,625	2.85	2.62	0.01
2023	4.00	32.00	986	1,547	2.79	2.56	0.01
2024	4.00	32.23	947	1,473	2.74	2.50	0.01
2025	4.00	32.45	909	1,403	2.68	2.44	0.01
2026	4.00	32.68	872	1,336	2.63	2.38	0.01
2027	4.00	32.91	838	1,272	2.58	2.33	0.01
2028	4.00	33.14	804	1,212	2.53	2.28	0.01
2029	4.00	33.37	772	1,154	2.48	2.23	0.01
2030	4.00	33.61	741	1,099	2.43	2.18	0.01

Supplementary Table 13. Germany, prospects for $\beta = .950$ and 20% rebate.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	2.92	0.01
2016	4.00	30.48	1,312	2,178	3.18	2.88	0.01
2017	4.00	30.69	1,260	2,074	3.18	2.84	0.01
2018	4.00	30.91	1,209	1,975	3.11	2.77	0.01
2019	4.00	31.12	1,161	1,881	3.04	2.70	0.01
2020	4.00	31.34	1,115	1,791	2.97	2.63	0.01
2021	4.00	31.56	1,070	1,706	2.91	2.57	0.01
2022	4.00	31.78	1,027	1,625	2.85	2.51	0.01
2023	4.00	32.00	986	1,547	2.79	2.45	0.01
2024	4.00	32.23	947	1,473	2.74	2.40	0.01
2025	4.00	32.45	909	1,403	2.68	2.34	0.01
2026	4.00	32.68	872	1,336	2.63	2.29	0.01
2027	4.00	32.91	838	1,272	2.58	2.24	0.01
2028	4.00	33.14	804	1,212	2.53	2.19	0.01
2029	4.00	33.37	772	1,154	2.48	2.15	0.01
2030	4.00	33.61	741	1,099	2.43	2.11	0.01

Supplementary Table 14. Germany, prospects for $\beta = .950$ and 30% rebate.

Year	r [%]	CF [%]	SP_e [€/kW]	SP_h [€/kW]	p_e [€¢/kWh]	p_h [€/kg]	k_h [-]
2015	4.00	30.27	1,367	2,287	3.18	2.76	0.01
2016	4.00	30.48	1,312	2,178	3.18	2.73	0.01
2017	4.00	30.69	1,260	2,074	3.18	2.70	0.01
2018	4.00	30.91	1,209	1,975	3.11	2.63	0.01
2019	4.00	31.12	1,161	1,881	3.04	2.57	0.01
2020	4.00	31.34	1,115	1,791	2.97	2.51	0.01
2021	4.00	31.56	1,070	1,706	2.91	2.45	0.01
2022	4.00	31.78	1,027	1,625	2.85	2.40	0.01
2023	4.00	32.00	986	1,547	2.79	2.34	0.01
2024	4.00	32.23	947	1,473	2.74	2.29	0.01
2025	4.00	32.45	909	1,403	2.68	2.24	0.01
2026	4.00	32.68	872	1,336	2.63	2.20	0.01
2027	4.00	32.91	838	1,272	2.58	2.15	0.01
2028	4.00	33.14	804	1,212	2.53	2.11	0.01
2029	4.00	33.37	772	1,154	2.48	2.07	0.01
2030	4.00	33.61	741	1,099	2.43	2.03	0.01

Supplementary Table 15. Texas, prospects for $\beta = .975$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.34	3.35	0.29
2017	6.00	35.10	1,471	1,822	2.58	3.39	0.30
2018	6.00	35.34	1,412	1,735	2.84	3.44	0.30
2019	6.00	35.59	1,356	1,652	3.10	3.49	0.31
2020	6.00	35.84	1,301	1,573	3.37	3.55	0.31
2021	6.00	36.09	1,249	1,498	3.65	3.61	0.32
2022	6.00	36.34	1,199	1,427	3.49	3.48	0.32
2023	6.00	36.59	1,151	1,359	3.34	3.35	0.32
2024	6.00	36.85	1,105	1,294	3.19	3.23	0.33
2025	6.00	37.10	1,061	1,232	3.05	3.12	0.33
2026	6.00	37.36	1,019	1,173	2.92	3.01	0.33
2027	6.00	37.62	978	1,118	2.80	2.90	0.33
2028	6.00	37.88	939	1,064	2.68	2.80	0.34
2029	6.00	38.14	901	1,013	2.46	2.71	0.34
2030	6.00	38.40	865	965	2.46	2.62	0.34

Supplementary Table 16. Texas, prospects for $\beta = .950$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.36	3.35	0.29
2017	6.00	35.10	1,471	1,822	2.62	3.38	0.29
2018	6.00	35.34	1,412	1,735	2.89	3.42	0.29
2019	6.00	35.59	1,356	1,652	3.17	3.47	0.29
2020	6.00	35.84	1,301	1,573	3.46	3.52	0.30
2021	6.00	36.09	1,249	1,498	3.75	3.58	0.30
2022	6.00	36.34	1,199	1,427	3.61	3.44	0.30
2023	6.00	36.59	1,151	1,359	3.47	3.31	0.30
2024	6.00	36.85	1,105	1,294	3.33	3.19	0.30
2025	6.00	37.10	1,061	1,232	3.21	3.07	0.30
2026	6.00	37.36	1,019	1,173	3.08	2.96	0.30
2027	6.00	37.62	978	1,118	2.97	2.86	0.30
2028	6.00	37.88	939	1,064	2.85	2.75	0.30
2029	6.00	38.14	901	1,013	2.75	2.66	0.30
2030	6.00	38.40	865	965	2.65	2.56	0.30

Supplementary Table 17. Texas, prospects for $\beta = .925$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.38	3.34	0.28
2017	6.00	35.10	1,471	1,822	2.66	3.37	0.28
2018	6.00	35.34	1,412	1,735	2.95	3.40	0.28
2019	6.00	35.59	1,356	1,652	3.24	3.45	0.28
2020	6.00	35.84	1,301	1,573	3.54	3.50	0.28
2021	6.00	36.09	1,249	1,498	3.85	3.55	0.28
2022	6.00	36.34	1,199	1,427	3.71	3.41	0.28
2023	6.00	36.59	1,151	1,359	3.58	3.28	0.28
2024	6.00	36.85	1,105	1,294	3.45	3.15	0.27
2025	6.00	37.10	1,061	1,232	3.33	3.03	0.27
2026	6.00	37.36	1,019	1,173	3.21	2.92	0.27
2027	6.00	37.62	978	1,118	3.09	2.81	0.27
2028	6.00	37.88	939	1,064	2.98	2.71	0.26
2029	6.00	38.14	901	1,013	2.88	2.61	0.26
2030	6.00	38.40	865	965	2.78	2.52	0.26

Supplementary Table 18. Texas, prospects for $\beta = .950$ and $\xi = 2.50\%$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.37	3.35	0.29
2017	6.00	35.10	1,471	1,822	2.64	3.38	0.29
2018	6.00	35.34	1,412	1,735	2.92	3.42	0.29
2019	6.00	35.59	1,356	1,652	3.22	3.46	0.30
2020	6.00	35.84	1,301	1,573	3.52	3.51	0.30
2021	6.00	36.09	1,249	1,498	3.83	3.57	0.31
2022	6.00	36.34	1,199	1,427	3.69	3.43	0.31
2023	6.00	36.59	1,151	1,359	3.56	3.30	0.31
2024	6.00	36.85	1,105	1,294	3.44	3.17	0.31
2025	6.00	37.10	1,061	1,232	3.32	3.05	0.31
2026	6.00	37.36	1,019	1,173	3.21	2.94	0.31
2027	6.00	37.62	978	1,118	3.10	2.83	0.31
2028	6.00	37.88	939	1,064	3.00	2.72	0.31
2029	6.00	38.14	901	1,013	2.90	2.63	0.31
2030	6.00	38.40	865	965	2.80	2.53	0.31

Supplementary Table 19. Texas, prospects for $\beta = .950$ and $\xi = 5.00\%$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.38	3.35	0.29
2017	6.00	35.10	1,471	1,822	2.66	3.38	0.29
2018	6.00	35.34	1,412	1,735	2.95	3.42	0.30
2019	6.00	35.59	1,356	1,652	3.26	3.46	0.30
2020	6.00	35.84	1,301	1,573	3.58	3.50	0.30
2021	6.00	36.09	1,249	1,498	3.92	3.54	0.31
2022	6.00	36.34	1,199	1,427	3.80	3.40	0.31
2023	6.00	36.59	1,151	1,359	3.69	3.26	0.31
2024	6.00	36.85	1,105	1,294	3.58	3.13	0.31
2025	6.00	37.10	1,061	1,232	3.47	3.00	0.31
2026	6.00	37.36	1,019	1,173	3.37	2.88	0.32
2027	6.00	37.62	978	1,118	3.28	2.76	0.32
2028	6.00	37.88	939	1,064	3.19	2.65	0.32
2029	6.00	38.14	901	1,013	3.11	2.54	0.32
2030	6.00	38.40	865	965	3.03	2.43	0.32

Supplementary Table 20. Texas, prospects for $\beta = .950$ and $\xi = 7.50\%$.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.53	0.29
2016	6.00	34.85	1,532	1,913	2.38	3.35	0.29
2017	6.00	35.10	1,471	1,822	2.68	3.38	0.29
2018	6.00	35.34	1,412	1,735	2.99	3.41	0.30
2019	6.00	35.59	1,356	1,652	3.31	3.45	0.30
2020	6.00	35.84	1,301	1,573	3.66	3.48	0.31
2021	6.00	36.09	1,249	1,498	4.02	3.51	0.31
2022	6.00	36.34	1,199	1,427	3.92	3.36	0.31
2023	6.00	36.59	1,151	1,359	3.83	3.21	0.32
2024	6.00	36.85	1,105	1,294	3.74	3.06	0.32
2025	6.00	37.10	1,061	1,232	3.66	2.91	0.32
2026	6.00	37.36	1,019	1,173	3.59	2.77	0.32
2027	6.00	37.62	978	1,118	3.51	2.63	0.33
2028	6.00	37.88	939	1,064	3.45	2.48	0.32
2029	6.00	38.14	901	1,013	3.39	2.34	0.32
2030	6.00	38.40	865	965	3.33	2.20	0.33

Supplementary Table 21. Texas, prospects for $\beta = .950$ and 10% rebate.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.34	0.30
2016	6.00	34.85	1,532	1,913	2.36	3.17	0.30
2017	6.00	35.10	1,471	1,822	2.62	3.21	0.30
2018	6.00	35.34	1,412	1,735	2.89	3.26	0.31
2019	6.00	35.59	1,356	1,652	3.17	3.31	0.31
2020	6.00	35.84	1,301	1,573	3.46	3.37	0.31
2021	6.00	36.09	1,249	1,498	3.75	3.44	0.32
2022	6.00	36.34	1,199	1,427	3.61	3.31	0.32
2023	6.00	36.59	1,151	1,359	3.47	3.18	0.31
2024	6.00	36.85	1,105	1,294	3.33	3.07	0.32
2025	6.00	37.10	1,061	1,232	3.21	2.96	0.32
2026	6.00	37.36	1,019	1,173	3.08	2.85	0.31
2027	6.00	37.62	978	1,118	2.97	2.75	0.31
2028	6.00	37.88	939	1,064	2.85	2.65	0.31
2029	6.00	38.14	901	1,013	2.75	2.56	0.31
2030	6.00	38.40	865	965	2.65	2.47	0.31

Supplementary Table 22. Texas, prospects for $\beta = .950$ and 20% rebate.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	3.15	0.32
2016	6.00	34.85	1,532	1,913	2.36	2.99	0.32
2017	6.00	35.10	1,471	1,822	2.62	3.04	0.32
2018	6.00	35.34	1,412	1,735	2.89	3.09	0.32
2019	6.00	35.59	1,356	1,652	3.17	3.15	0.32
2020	6.00	35.84	1,301	1,573	3.46	3.22	0.33
2021	6.00	36.09	1,249	1,498	3.75	3.29	0.33
2022	6.00	36.34	1,199	1,427	3.61	3.17	0.33
2023	6.00	36.59	1,151	1,359	3.47	3.05	0.33
2024	6.00	36.85	1,105	1,294	3.33	2.94	0.33
2025	6.00	37.10	1,061	1,232	3.21	2.84	0.33
2026	6.00	37.36	1,019	1,173	3.08	2.74	0.33
2027	6.00	37.62	978	1,118	2.97	2.64	0.33
2028	6.00	37.88	939	1,064	2.85	2.55	0.33
2029	6.00	38.14	901	1,013	2.75	2.46	0.33
2030	6.00	38.40	865	965	2.65	2.38	0.33

Supplementary Table 23. Texas, prospects for $\beta = .950$ and 30% rebate.

Year	r [%]	CF [%]	SP_e [\$/kW]	SP_h [\$/kW]	p_e [\$¢/kWh]	p_h [\$/kg]	k_h [-]
2015	6.00	34.61	1,596	2,009	2.55	2.95	0.34
2016	6.00	34.85	1,532	1,913	2.36	2.80	0.34
2017	6.00	35.10	1,471	1,822	2.62	2.86	0.34
2018	6.00	35.34	1,412	1,735	2.89	2.92	0.34
2019	6.00	35.59	1,356	1,652	3.17	2.99	0.34
2020	6.00	35.84	1,301	1,573	3.46	3.06	0.35
2021	6.00	36.09	1,249	1,498	3.75	3.14	0.35
2022	6.00	36.34	1,199	1,427	3.61	3.02	0.35
2023	6.00	36.59	1,151	1,359	3.47	2.92	0.35
2024	6.00	36.85	1,105	1,294	3.33	2.81	0.35
2025	6.00	37.10	1,061	1,232	3.21	2.71	0.35
2026	6.00	37.36	1,019	1,173	3.08	2.62	0.35
2027	6.00	37.62	978	1,118	2.97	2.53	0.35
2028	6.00	37.88	939	1,064	2.85	2.45	0.35
2029	6.00	38.14	901	1,013	2.75	2.36	0.34
2030	6.00	38.40	865	965	2.65	2.29	0.35

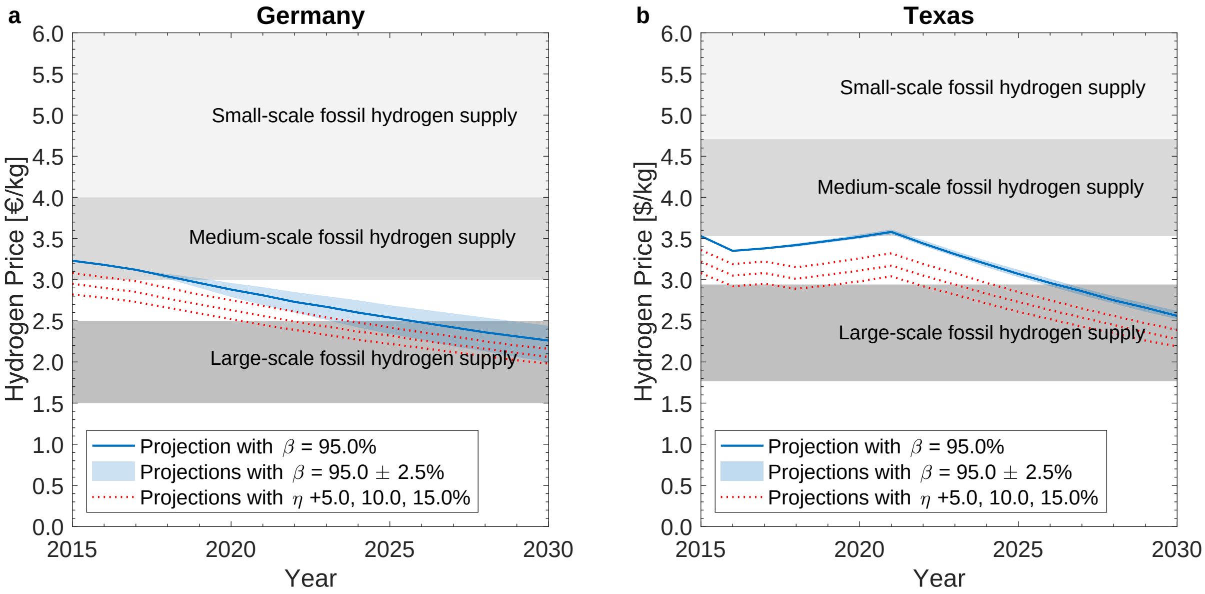
Supplementary Note 2

Here we discuss the sensitivity of the break-even price for hydrogen production from renewable electricity. Most important is that the PtG facility is sized optimally in capacity relative to the renewable energy source, because both energy systems are dominated in their economics by the upfront capacity investment. Figure 1 shows the sensitivity of the break-even price for hydrogen for various sizes of PtG.

Another major driver of our findings is the electricity price level at which the renewable energy source can sell its generated power. As the economic model in the main body of the paper shows, the economics of converting renewable electricity to hydrogen improves with the time intervals during the electricity price is below the conversion value for hydrogen. These periods may occur on account of either a low average or a high volatility of the electricity price. Figure 3 shows the sensitivity of the break-even price for hydrogen for both factors. Specifically, the shaded blue areas illustrate the change in break-even prices for an average electricity price that declines 2.5% faster or slower than our estimated baseline decline. The dotted lines show the sensitivity for an increased volatility of the electricity price. To keep the average electricity price unaffected by changes in volatility, we model the price to increase by an additional ξ% during the hours of above average prices and to decrease by an offsetting percentage during the hours of below average prices.

Since the capital expenditures constitute a large part of the overall system costs, the break-even price for hydrogen is also sensitive to the system price of a PtG facility. While the expected decline over the coming years is included in the section on the prospects for renewable hydrogen production in the main text, Figure 4 displays the trajectory of break-even prices for hydrogen with the system price of PtG reduced by rebates of 10, 20, and 30%.

Finally, Supplementary Figure 1 provides the change in break-even prices for hydrogen, assuming an improved conversion rate, η, by 5.0, 10.0, and 15.0%. The figure shows that every increment of 5% would accelerate the cost competitiveness of renewable hydrogen production with large-scale industrial supply by about 1.5 years.



Supplementary Figure 1. Prospects for renewable hydrogen production. a, b, The impact of improved conversion efficiencies on the break-even price of renewable hydrogen in Germany (**a**) and Texas (**b**) relative to the benchmark price for fossil hydrogen supply.

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