Buffering the Volatility in Power Markets: Reversible Power-to-Gas Systems

Gunther Glenk[*]
School of Business, University of Mannheim
MIT CEEPR, Massachusetts Institute of Technology
glenk@uni-mannheim.de

Stefan Reichelstein
School of Business, University of Mannheim
Graduate School of Business, Stanford University
reichelstein@uni-mannheim.de

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Abstract

Recent advances in Power-to-Gas technologies in terms of acquisition cost and conversion efficiency have been accompanied by the availability of inexpensive surplus electricity from volatile wholesale power markets at select times. Here we examine the economics of reversible Power-to-Gas systems that can convert electricity to hydrogen or operate in the reverse direction to deliver electricity during times of high power prices. Our model framework is applied to the current market environment in both Germany and Texas. We find that the reversibility feature of solid oxide fuel cells makes such systems already competitive at current hydrogen prices, provided the fluctuations in electricity prices are as pronounced as currently observed in Texas. We project that if recent technological improvements for solid oxide cells continue over the coming decade, the flexibility inherent in reversible Power-to-Gas systems would leave investments in such systems economically viable even at substantially lower hydrogen prices.

Keywords: Power Markets, Hydrogen, Power-to-Gas, Energy Storage

1 Introduction

The large-scale deployment of intermittent energy resources, like wind and solar, has generally resulted in deregulated power markets becoming more volatile[1;2]. To balance supply and demand for electricity in real time, energy storage in the form of batteries and pumped hydro power is playing an increasingly important role[3–5]. At the same time, hydrogen is increasingly viewed as an energy carrier with broad application potential in decarbonized energy economies[6–8]. Power-to-Gas (PtG) systems that split water molecules into hydrogen and oxygen via electrolysis can rapidly absorb significant amounts of surplus electricity during times of low prices[9–12]. This buffering capacity of PtG systems can be enhanced further by systems that are also capable of operating in the reverse direction, converting hydrogen to electricity during periods of high power prices[13–15].

Reversible PtG systems can be designed in a *modular* manner, for instance by combining an electrolyzer for hydrogen production with a fuel cell or gas turbine for power generation[7;16;17]. While electrolyzers have been found to become increasingly competitive in producing hydrogen[18;19], fuel cells and gas turbines have so far been regarded as too expensive for wholesale market applications[14;20]. Alternatively, solid oxide fuel cells constitute *integrated* PtG systems, as the same equipment can be utilized to deliver either hydrogen or electricity depending on the state of electricity prices at any given point in time. Solid oxide cells have been brought to market recently. Their reversibility feature has been established in several studies and demonstration projects[21–23].

This paper first presents a generic analytical model to examine the economic viability of reversible PtG systems. We then calibrate the model in the context of the electricity markets in Germany and Texas. Despite improvements in the cost and conversion efficiency of modular PtG systems[24;25], we conclude that there is no economic case, either now or in the foreseeable future, for investing in modular systems that convert hydrogen back to electricity. Integrated PtG systems, however, are competitive at current hydrogen prices, given sufficient variation in daily electricity prices, as is already encountered in the Texas market. While it is efficient for such systems to mostly produce hydrogen, they can also take advantage of high power prices to boost the supply of electricity. We furthermore conclude that due to improved capacity utilization the integrated system is positioned more competitively than an electrolyzer on its own. Finally, if recent trends regarding the acquisition cost of solid oxide cells continue, such systems will remain economically viable even with substantially lower hydrogen prices in the future. The reason is that their inherent flexibility allows the integrated reversible PtG systems to respond to lower hydrogen prices by engaging more frequently in power generation.

2 Real-time Operation of Reversible Power-to-Gas

We examine the economics of reversible PtG systems that can (i) produce hydrogen via water electrolysis and (ii) combine hydrogen with oxygen to obtain electricity and water[26]. We refer to such systems as *modular* if both production processes can be carried out at the same time; for instance, the system combines an electrolyzer for hydrogen production with a fuel cell or gas turbine for the reverse operation. In contrast, we refer to a reversible fuel cell, such as a solid oxide cell, as an *integrated* reversible PtG system if at any point in time it can run in either one direction or remain idle. Time is modeled as a continuous variable t ranging from 0 to 8,760 hours per year. Let $q(t)$ denote the wholesale market price for electricity per kilowatt hour (kWh) at time t. We initially assume that the annual distribution of power prices remains constant across the lifetime of the system.

If the modular system generates hydrogen at time t, it earns a "conversion price" consisting of the market price of hydrogen, p, per kilogram (kg) multiplied with the conversion rate of going from electricity to hydrogen (in kg/kWh). The corresponding parameter η_h^o represents the kg of hydrogen that can be generated from 1 kWh of electricity. The variable cost of hydrogen generation equals $q(t)$ plus a cost increment w_h^o per kWh that accounts for consumable inputs, like water and reactants for deionizing the water, as well as any purchasing mark-ups on the wholesale price of electricity. All symbols and acronyms are listed in Supplementary Table 1.

For the purposes of our economic analysis, there is no loss of generality in normalizing capacity investments for either the modular or the integrated system to 1 kilowatt (kW) of electricity input or output. Furthermore, the electrolyzer and fuel cell technologies we consider in the empirical part allow for rapid up- or down ramping[27]. The corresponding capacity factors, i.e., the percentage of the available capacity utilized at time t, can thus be chosen anywhere on the interval $[0, 1]$. We denote these capacity factors by $CF(t)$, and note that, in the context of our model, optimal utilization will always entail a "bang-bang" type solution so that $CF(t)$ is always equal to zero or one.

Given a hydrogen price, p, the contribution margin attained with the modular reversible

PtG system from one kWh of hydrogen generation at time t is:

$$CM_h^o(t|p) = \big[\eta_h^o \cdot p - q(t) - w_h^o\big] \cdot CF_h^o(t|p). \tag{1}$$

Conversely, if the modular system generates electricity, it earns $q(t)$ and incurs a variable cost that comprises p and an incremental cost, w_e^o, per kWh of electricity for transporting hydrogen to the reversible PtG system. To account for efficiency losses, p is divided by the conversion rate for power generation, η_e^o (in kWh/kg). The contribution margin of electricity generation per kWh at time t then becomes:

$$CM_e^o(t|p) = \big[q(t) - \frac{p}{\eta_e^o} - w_e^o\big] \cdot CF_e^o(t|p). \tag{2}$$

Efficient utilization of the existing capacity is obtained if the capacity factors are at each point in time chosen to maximize the total available contribution margin. While the modular system can run at full capacity in both directions, the 1st Law of Thermodynamics stipulates that the overall round-trip efficiency must satisfy the inequality $\eta_h^o \cdot \eta_e^o \leq 1$. Consequently, at most one of the terms $\big[\eta_h^o \cdot p - q(t) - w_h^o\big]$ or $\big[q(t) - \frac{p}{\eta_e^o} - w_e^o\big]$ can be positive for any given values $w_h^o, w_e^o \geq 0$. Efficient system utilization thus implies that the capacity factors be chosen so that $CF_h^o(t|p) \cdot CF_e^o(t|p) = 0$, consistent with the illustration in Figure 1 (see *Methods* for formal derivations). Finally, let $CM^o(p)$ denote the average optimized contribution margin obtained as the sum of the optimized contribution margins, $CM_h^o(p)$ and $CM_e^o(p)$, in (1) and (2), respectively, when aggregated across the hours of a year (see *Methods* for details).

For the integrated system, the economic trade-off is principally the same, except that the incremental cost and conversion rates may differ and instead assume the values w_h, w_e, η_h, and η_e, respectively. By construction, the integrated system can only run in at most one direction at any point in time and, therefore, faces the technical, rather than economic, "complementary slackness" condition $CF_h(t|p) \cdot CF_e(t|p) = 0$ for all t. The corresponding contribution margins are:

$$CM_h(t|p) = \big[\eta_h \cdot p - q(t) - w_h\big] \cdot CF_h(t|p), \tag{3}$$

for hydrogen production, and

$$CM_e(t|p) = \big[q(t) - \frac{p}{\eta_e} - w_e\big] \cdot CF_e(t|p), \tag{4}$$

for electricity. The capacity factors that maximize the sum of the contribution margins in (3) and (4), subject to the complementary slackness constraint, are denoted by $CF_h^*(t|p)$ and $CF_e^*(t|p)$, respectively. Given these capacity factors, we denote by $CM(p)$ the optimized aggregate contribution margin which is obtained as the total margin obtained after integrating (3) and (4) across the hours of the year.

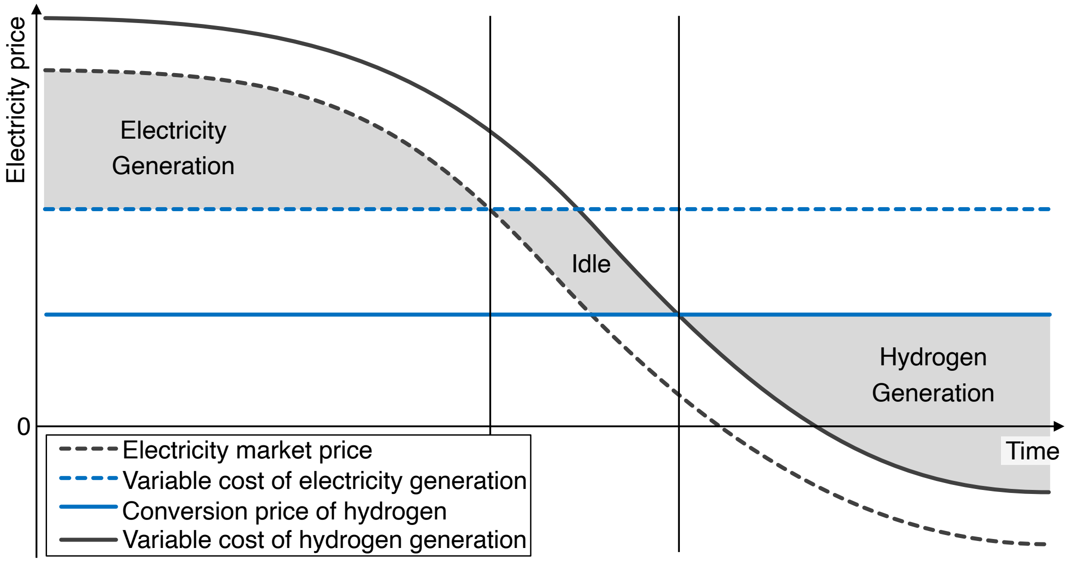

Figure 1: **Contribution margins of a reversible Power-to-Gas system.** The figure illustrates the three alternative operating modes for a reversible PtG system that emerge for varying electricity prices. Wholesale electricity prices can turn negative as a result of surplus energy being supplied to the grid at certain hours.

3 Cost Competitiveness and the Value of Reversibility

A reversible Power-to-Gas system is said to be cost competitive if the required upfront investment in equipment yields a positive net-present value in terms of discounted future cash flows. The discounted annual stream of optimized contribution margin of the system must then at least cover the initial equipment expenditure. For direct comparison, it will be convenient to capture this economic trade-off on a levelized basis. Analogous to the commonly known levelized cost of electricity, the Levelized Fixed Cost (LFC) of a reversible PtG system reflects the unit acquisition cost of the system per kWh, including applicable fixed operating costs, corporate income taxes, and the cost of debt and equity[28;29].

For the modular system, the levelized fixed cost per kWh for the electrolyzer is denoted by LFC_h^o. As shown in *Methods*, the Power-to-Gas subsystem is cost competitive (positive net-present value) if and only if at the prevailing market price for hydrogen, p:

$$CM_h^o(p) - LFC_h^o > 0.$$

Since the contribution margin from hydrogen is increasing in the selling price of hydrogen, there exists a unique break-even price, p_h^o, such that Power-to-Gas will be cost competitive whenever $p \geq p_h^o$. Similarly, the Gas-to-Power (GtP) subsystem is cost competitive whenever:

$$CM_e^o(p) - LFC_e^o > 0,$$

with LFC_e^o denoting the corresponding levelized fixed cost per kWh. Since the contribution margin from producing electricity is decreasing in the input price for hydrogen, p, there also exists a unique break-even price, p_e^o, below which GtP will be cost competitive.

By design, investors in a modular system retain the option of acquiring only one of the two subsystems. We therefore call the modular system cost competitive if at least one of its subsystems is cost competitive. In addition, the *reversibility* feature of the system is said to be *valuable* if both subsystems have positive net-present value on their own. The following finding links cost competitiveness and the value of reversibility to the prevailing market price of hydrogen.

Finding 1: *The modular reversible PtG system is cost competitive if and only if at the prevailing hydrogen market price, p, either $p > p_h^o$ or $p < p_e^o$. Reversibility of the modular system is valuable if and only if $p \in [p_h^o, p_e^o]$.*

Figure 2a illustrates the setting of a modular reversible PtG system that is cost competitive and for which reversibility is valuable. Note that reversibility of the modular system cannot be of value unless $p_h^o < p_e^o$.

For the integrated reversible PtG system, the levelized fixed cost per kWh of the reversible fuel cell is denoted by LFC. Cost competitiveness of the integrated system then requires that the optimized aggregate contribution margin, $CM(p)$, exceeds LFC. The reversibility of the integrated system is said to be valuable if at the prevailing market price of hydrogen, p, investment in the reversible fuel cell is cost competitive and, furthermore, the system operates in both directions for select hours of the year, i.e., both sets $\{t|CF_h^*(t|p) > 0\}$ and $\{t|CF_e^*(t|p) > 0\}$ have positive length across the hours of the year.

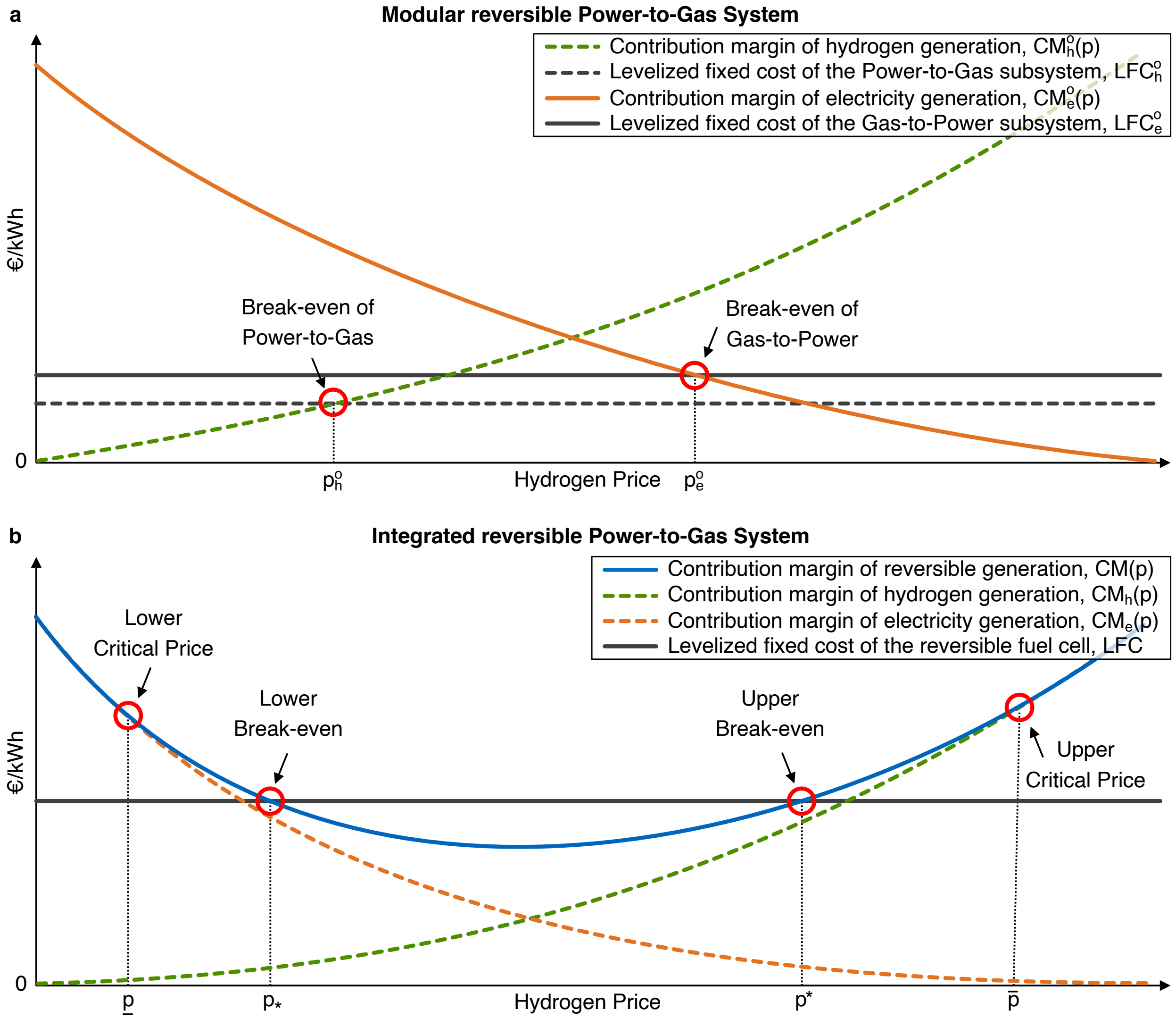

Figure 2: **Economics of a reversible Power-to-Gas system. a,b,** The figure illustrates the potential cost competitiveness and value of reversible operation in terms of the respective break-even prices of (**a**) a modular reversible Power-to-Gas system, and (**b**) an integrated reversible Power-to-Gas system.

Figure 2b illustrates a setting in which the reversibility feature of the integrated reversible PtG system is valuable. We note that when viewed as a function of p, the optimized contribution margin, $CM(\cdot)$, is drawn as a U-shaped curve. This follows directly from the convexity of this function in p (see *Methods*, combined with the observation that $CM(p)$ is increasing for large values of p and again increasing as p becomes small, possibly negative. The U-shape of $CM(\cdot)$ implies that there exist at most two break-even points at which $CM(p) = LFC$. These points are denoted by p_* and p^*, respectively.

To examine the value of reversibility, suppose hypothetically that the integrated system could operate in only one direction. For instance, suppose the system is constrained to only produce hydrogen (i.e., $CF_e(t|p)$ in (4) is set identically equal to zero). For sufficiently large values of p, there then exists a critical value denoted by $\bar{p}$ such that $CM(\bar{p}) = CM_h(\bar{p})$. This equality holds for all $p > \bar{p}$. Conversely, there exists a lower critical price below which only electricity generation would be valuable, that is, $CM(p) = CM_e(p)$ for all $p \leq \underline{p}$.

Finding 2: *The integrated reversible PtG system is cost competitive if and only if the prevailing hydrogen market price, p, does not fall into the range $[p_*, p^*]$. Reversibility of the integrated system is valuable if and only if either $p \in (\underline{p}, p_*)$ or $p \in (p^*, \bar{p})$.*

Finding 2 shows that a reversible fuel cell is cost competitive if the market price of hydrogen moves either into an upper or lower range relative to the price at which the optimized contribution margin reaches its minimum. For the case where $p \in (p^*, \bar{p})$, Figure 2b depicts the possibility that the reversible fuel cell primarily generates hydrogen, but also operates bi-directionally. Such systems could create an effective buffer against the intermittency of renewables when power is absorbed from the electricity market for hydrogen conversion, yet occasionally electricity is generated at hours of limited power supply and correspondingly high power prices. The range of hydrogen prices at which an integrated system generates both outputs hinges, in addition to cost, on the round-trip efficiency and the volatility in power prices (Figure 1).

An implicit assumption underlying Finding 2 and Figure 2b is that LFC exceeds the minimum of the $CM(\cdot)$ curve, for otherwise the break-even prices p_* and p^* do not exist (we ignore the non-generic scenario in which there is exactly one break-even price at a tangency point). In case $LFC < CM(\cdot)$ for all p, the integrated reversible PtG system will always be cost competitive and reversibility will be of value for all hydrogen prices within the interval $(\underline{p}, \bar{p})$. In this case, the flexibility of the integrated reversible PtG system allows it to compensate for any decline in the prevailing market price of hydrogen by turning to electricity production for a larger share of the available time.

4 Current Economics of Reversible Power-to-Gas

To apply the preceding model framework, we calibrate the model parameters in the current market environment of Germany and Texas. Both jurisdictions have recently deployed considerable amounts of renewable energy[30]. While Germany has maintained coal and natural gas plants as capacity reserves, Texas has retired several conventional generators[31]. The average wholesale electricity price in 2019 was comparable for both jurisdictions, yet power prices in Texas exhibited much higher volatility. As detailed further in *Methods* and Supplementary Tables 2–5, our calculations rely on a range of data sources collected from journal articles, industry data, and publicly available reports. Table 1 summarizes our key parameter estimates.

Table 1: **Main input variables.**

	Germany	**Texas**
Modular Reversible PtG System		
Electrolysis: System price	1,606 €/kW	1,799 \$/kW
Electrolysis: Conversion rate to hydrogen	0.019 kg/kWh	0.019 kg/kWh
Gas Turbine: System price	1,000 €/kW	1,199 \$/kW
Gas Turbine: Conversion rate to electricity	20.00 kWh/kg	20.00 kWh/kg
Useful lifetime	25 years	25 years
Integrated Reversible PtG System		
System price	2,243 €/kW	2,512 \$/kW
Conversion rate to hydrogen	0.023 kg/kWh	0.023 kg/kWh
Conversion rate to electricity	20.00 kWh/kg	20.00 kWh/kg
Useful lifetime	15 years	15 years
Either System		
Average electricity price (2019)	3.77 €¢/kWh	3.77 \$¢/kWh
Cost of capital	4.00%	6.00%

Our numbers for the modular PtG system are based on a polymer electrolyte membrane (PEM) electrolyzer and a combined-cycle gas turbine. Stationary fuel cells based on PEM technology currently have about the same conversion rate as combined-cycle gas turbines but entail higher system prices[20]. PEM electrolyzers could, in principle, also operate reversibly but less flexibly and, therefore, such electrolyzers are commonly built for one-directional operation[32;33]. For the integrated reversible PtG system, we consider solid oxide cells (SOC) that function as reversible fuel cells[32;33].

The investing party is assumed to have access to the day-ahead wholesale market for electricity. In order to accelerate the transition towards renewable energy, the German government recently decided that electricity purchases for water electrolysis are exempted from certain taxes and fees paid by industrial customers.[34] In Texas, the investing party is assumed to be able to purchase electricity at wholesale prices subject to a markup, as imposed by suppliers like Griddy (see Supplementary Tables 4–5).

We first determine the hydrogen break-even prices. To assess the cost competitiveness of each (sub-)system, we then compare the break-even prices to prevailing transaction prices for hydrogen supply. These values are applicable benchmarks for hydrogen as both an input and an output when the PtG (or GtP) system can be installed nearby a hydrogen or electricity customer. Market prices currently fall into three segments that vary with purity and scale (volume): large-scale supply between 1.5–2.5 €/kg, medium-scale between 3.0–4.0 €/kg, and small-scale above 4.0 €/kg[35].

Our calculations yield break-even prices for the modular electrolyzer (p_h^o) of 3.29 €/kg in Germany and 2.94 \$/kg in Texas, while the break-even prices for the modular gas turbine (p_e^o) are 0.54 €/kg in Germany and 1.30 \$/kg in Texas (Table 2, see Supplementary Tables 6–7 for details). The much higher break-even price for the GtP system in Texas must be attributed to the higher volatility in Texas wholesale electricity prices, which in 2019 exceeded 0.15 \$¢/kWh on a regular basis.

Finding 1 implies that modular Power-to-Gas conversion is cost competitive in both jurisdictions relative to the prices paid for small- and medium-scale hydrogen supply, while the GtP subsystem is not. Furthermore, the reversibility of the modular system cannot be valuable relative to any prevailing market price for hydrogen because $p_h^o > p_e^o$ in both jurisdictions. Our results here confirm the commonly held view that one-directional GtP systems currently are not economically viable[4;14;20].

Table 2: **Current economics.**

Break-even prices	**Germany**	**Texas**
Modular Reversible PtG System		
Break-even price of Power-to-Gas: p_h^o	3.19 €/kg	2.86 \$/kg
Break-even price of Gas-to-Power: p_e^o	0.54 €/kg	1.30 \$/kg
Integrated Reversible PtG System		
Upper break-even price: p^*	3.41 €/kg	2.59 \$/kg
Lower break-even price: p_*	0.02 €/kg	-0.01 \$/kg
Upper critical price: $\bar{p}$	2.43 €/kg	>5.0 \$/kg
Lower critical price: $\underline{p}$	-1.81 €/kg	0.59 \$/kg

For the integrated system, our calculations yield break-even prices of 0.02 €/kg for p_* and 3.41 €/kg for p^* in Germany, while the break-even prices in Texas are -0.01 \$/kg and 2.59 \$/kg , respectively (Table 2). The substantially smaller p^* in Texas reflects the higher volatility in wholesale power prices. By Finding 2, the integrated system is thus cost competitive when hydrogen is sold to small- and medium-scale customers in Germany. In Texas, cost competitiveness is achieved even relative to a hydrogen price of at least \$ 2.59 per kg, a value that is borderline for industrial-scale supply.

Regarding the value of reversibility for the integrated system, our calculations yield upper and lower critical prices ($\underline{p}$ and $\bar{p}$) of -1.81 €/kg and 2.43 €/kg, respectively, in Germany. In Texas, the corresponding values are 0.59 \$/kg for $\underline{p}$, while $\bar{p}$ exceeds 5.0 \$/kg. Because the hydrogen prices for medium scale supply fall "comfortably" into the range $(p^*, \bar{p}) = (2.59, 5.0)$, we conclude that the reversibility of the integrated PtG system is already valuable in the current Texas environment. Contrary to frequently articulated views in the popular press, the generation of electric power from hydrogen is therefore already economical, provided such generation is part of an integrated PtG system that mainly produces hydrogen yet only occasionally operates in the reverse direction to generate electricity. Such systems can therefore be effective in buffering the increasing volatility in power markets resulting from the growing reliance on intermittent renewable energy sources.

Direct comparison of the modular one-sided and the integrated reversible PtG systems shows that the latter is already positioned more competitively despite its substantially higher systems price, as the break-even price of \$2.59 is below the corresponding \$2.86 per kg for the PEM electrolyzer.

5 Prospects for Reversible Power-to-Gas

Recent technological progress in reversible PtG systems suggests further improvements in terms of declining system prices and increasing conversion efficiencies[36–39]. System prices of PEM electrolyzers are forecast to decline at an annual rate of 4.77%, while conversion rates are likely to increase linearly to 0.023 kg/kWh by 2030[20;35]. For combined-cycle gas turbines, both of these parameters are expected to remain unchanged.

To assess the cost dynamics of the reversible fuel cell, we rely on a hand-collected data set described in *Methods*. Our estimate for the annual price decline amounts to 8.95%. The conversion rate of the reversible fuel cell is expected to increase linearly to 0.024 kg/kWh for hydrogen generation and 21.67 kWh/kg for power generation by 2030[20]. Our calculations are based on the current distribution of power prices to isolate the effects of falling system prices and improved conversion rates. A fall in the average of power prices in connection with rising price volatility, as previous studies suggest[40–42], would affect the economics of either system favorably.

Our model results in a trajectory of break-even prices through 2030 as shown in Figure 3 (see Supplementary Tables 8–9 for details). The green lines indicate that the modular electrolyzer is likely to become cost competitive even relative to the lower prices in the large-scale hydrogen market segment. This conclusion emerges sooner in Texas due to higher volatility in power prices. The break-even prices for the modular gas turbine, as depicted by the orange lines, are projected to remain unchanged. Even though the gap between p_h^o and p_e^o is shrinking, the reversibility feature of the modular system is unlikely to become valuable during the next decade.

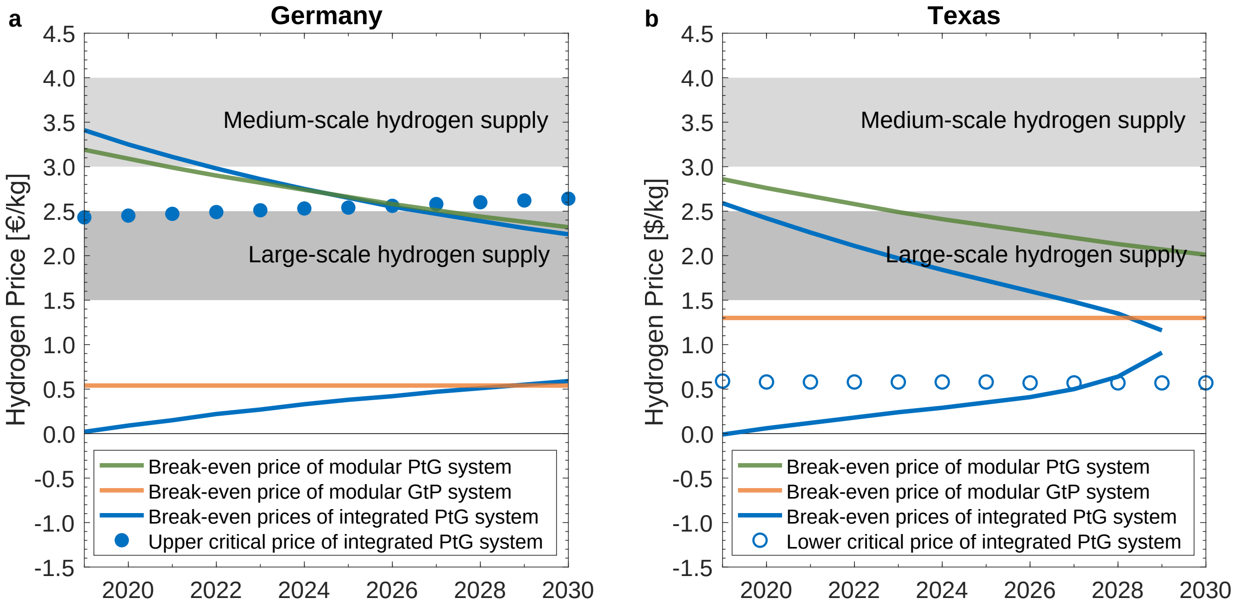

Figure 3: **Trajectory of break-even and critical hydrogen prices. a,b,** This figure contrasts the relevant hydrogen prices of modular and integrated reversible Power-to-Gas systems in (**a**) Germany and (**b**) Texas with the hydrogen prices attained in different market segments. The lower critical price of the integrated system in Germany is consistently below -1.5 €/kg. The upper critical price of the integrated system in Texas is consistently above 5.0 $/kg.

The integrated system, in contrast, is projected to become widely cost competitive for large-scale hydrogen supply in both jurisdictions as shown by the upper blue lines in Figure 3. We furthermore project the reversibility feature of the integrated system to become increasingly valuable in both jurisdictions as indicated by the falling upper blue lines. In fact, for Texas the range $[p_*, p^*]$ is evaporating within an eight-year time frame. As explained in the modeling section, this projection corresponds to a scenario where the flexibility inherent in the reversible fuel cell allows it to achieve an optimized contribution that exceeds the levelized fixed cost of the system, regardless of the prevailing hydrogen price.

In Germany, the reversibility feature of the integrated system is likely to deliver value starting in the second half of the coming decade. This can be seen in Figure 3a by comparing the upper blue line with the blue dots, which illustrate the trajectory of the upper critical prices ($\bar{p}$) for the reversible fuel cell. The reason is that, as the upper break-even price falls, the reversible PtG system will increasingly switch to power generation, as opposed to staying idle, when electricity prices peak (Figure 1).

6 Concluding Remarks

Reversible Power-to-Gas systems have the potential to buffer the growing volatility in electricity markets resulting from the large-scale deployment of renewable energy sources. Our analysis has demonstrated that recent advances in reversible fuel cells (solid oxide cells) already make such systems competitive relative to current hydrogen prices. By exploiting the fluctuations in hourly electricity prices, reversible PtG systems not only act as price buffers in electricity markets, they also broaden the supply sources for carbon-free hydrogen as an industrial input and general energy carrier. If recent trends in the acquisition cost of solid oxide cells continue over the next 5-10 years, our projections indicate that such systems will remain competitive even in the face of substantially lower hydrogen prices, as the system then adjusts by operating more often as a Gas-to-Power system.

Several promising avenues for future research emerge from our analysis. Earlier work has shown that the economics of electrolyzers can be improved by vertically integrating them with upstream renewable energy sources in order to achieve operational synergies[43]. It remains to be seen to what extent the addition of a renewable power source, beyond purchases from the grid, would improve the capacity utilization of a reversible PtG system and, therefore, lower the corresponding break-even values. Furthermore, if one views a reversible PtG system as an energy storage device, the natural question is how its cost compares to that of other storage technologies such as batteries or pumped hydro systems[1;3].

From a policy perspective, we note that our projections regarding the economic positioning of reversible PtG systems have relied on a regression model that presumes that cost declines are a function of calendar time. Yet, the literature on clean energy technologies, in particular renewable energy like solar PV and wind power, has shown that cost declines are not merely an exogenous function of time but instead are determined endogenously by the cumulative number of deployments of these systems. Policy makers should keep these long-term benefits in mind in adopting regulatory mechanisms intended to accelerate the pace of deployments for PtG systems.

7 Methods

Cost Dynamics of Solid Oxide Cells

We collected cost estimates from a range of information sources, including industry publications, academic articles in peer-reviewed journals and technical reports by agencies, consultancies and analysts. These documents were retrieved by searching the database Scopus and the web with Google's search engine using a combination of one of the five technology-specific keywords 'reversible electrolyzer', 'reversible fuel cell', 'solid oxide electrolysis cell', 'solid oxide fuel cell', or 'reversible power-to-gas' with the two economic keywords 'cost' and 'investment'. For industry statements, we also searched with the name of a manufacturer in combination with the economic keywords. For the Google search, we reviewed the top 100 search results. The review and the data set is documented in an Excel file available as part of the Supplementary Data.

The review yielded 211 sources, which we filtered by several criteria to ensure quality and timeliness. First, we excluded results published before the year 2000 and, for journal articles, results published in a journal with a rank below 0.5 in the Scimago Journal and Country Rank. The threshold of 0.5 showed to be effective for excluding articles published, for instance, in conference proceedings without peer-review. As for technical reports, we only included results that could convince through appearance, writing, clarity of methodology, and reputation of the author(s) or authoring organization(s). These measures removed 47 sources. Reviewing the resulting stock of sources, we further excluded sources that did not provide direct cost or efficiency data (49) and sources citing other articles as original sources (29). These citations were traced back to the original source. If the original was new, we added it to the pool. We further added sources that we found with a previous review[35] and that were new to the pool.

Our procedure left 86 sources with original data from industry or an original review of multiple sources and yielded 89 cost estimates. In case the sources issued range estimates, we took the arithmetic mean of the highest and the lowest value. The common currency is Euro and all data points in other currencies were converted using the average exchange rate of the respective year as provided by the European Central Bank. Regarding inflation, all historic cost estimates were adjusted using the HCPI of the Euro Zone as provided by the European Central Bank. The cost estimates were winsorized at a 1.0% level. Figure 4 shows the cost estimates and regression results.

Our hand-collected data yielded $N = 79$ price observations. We estimate the trajectory of system price by means of a univariate regression covering the years 2000–2019. The functional form of the regression is a constant elasticity model of the form:

$$v(i) = v(0) \cdot \beta^i,$$

with $v(i)$ representing the system price in year i. As shown in Figure 4, the resulting estimate for the annual price decline is 8.95% ($\beta = 0.9105$) with a 95% confidence interval of ±3.20% ($R^2 = 0.27$).

Economic Model

Step 1: Derivation of the Aggregate Contribution Margins

We begin with the derivation of the optimized aggregate contribution margin, $CM(p)$, that is attainable annually if the investor acquires a 1 kW system of the integrated reversible PtG system and the prevailing market price of hydrogen is p. By construction:

$$CM(p) = \frac{1}{m} \int_0^m \max_{CF_h(\cdot), CF_e(\cdot)} \{[\eta_h \cdot p - q(t) - w_h] \cdot CF_h(t|p) + [q(t) - \frac{p}{\eta_e} - w_e] \cdot CF_h(t|p)\} dt, \quad (5)$$

subject to $0 \leq CF_h(\cdot), CF_e(\cdot) \leq 1$ and the technical constraint that the reversible fuel cell can only run in one direction at any point in time. Thus $CF_h(\cdot) \cdot CF_e(\cdot) = 0$ for all t. The latter constraint, however, is not binding because $\eta_h \cdot \eta_e \leq 1$ (by the 1st Law of Thermodynamics) and, therefore, either $\eta_h \cdot p - q(t) - w_h \leq 0$ or $q(t) - \frac{p}{\eta_e} - w_e \leq 0$, or both, for all t. It follows that $CM(p)$ is additively separable and can be written as $CM(p) = CM_h(p) + CM_e(p)$, with:

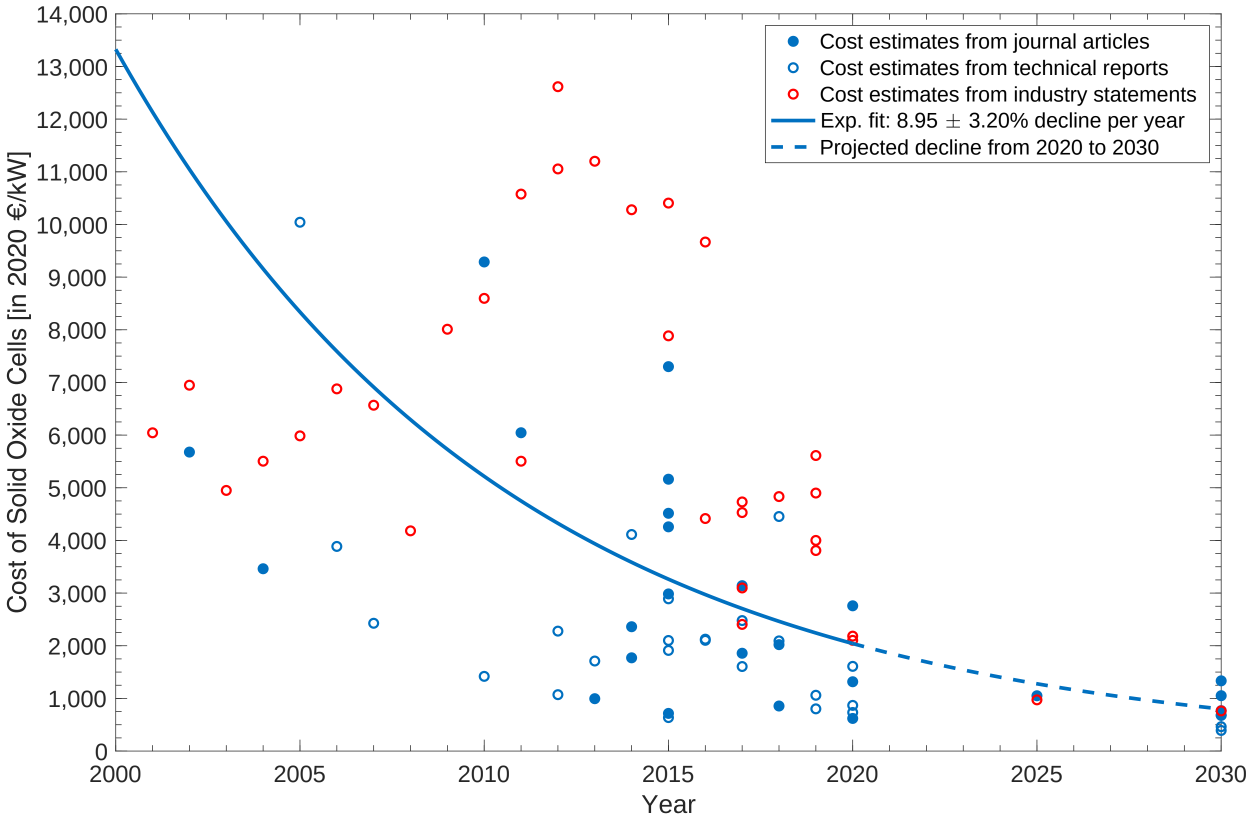

Figure 4: **Cost of solid oxide cells.** Cost data are from multiple sources. The univariate regression suggests a constant cost decline over the coming years.

$$\begin{aligned} CM_h(p) &= \frac{1}{m} \int_0^m \left[\eta_h \cdot p - q(t) - w_h\right] \cdot CF_h^*(t|p)dt, \\ CM_e(p) &= \frac{1}{m} \int_0^m \left[q(t) - \frac{p}{\eta_e} - w_e\right] \cdot CF_e^*(t|p)dt, \end{aligned} \tag{6}$$

and $CF_h^*(t|p) = 1$ if and only if $\eta_h \cdot p - q(t) - w_h \geq 0$. Similarly $CF_e^*(t|p) = 1$ if and only if $q(t) - \frac{p}{\eta_e} - w_e \geq 0$.

For the modular reversible PtG systems, the aggregate optimized contribution margins $CM_h^o(p)$ and $CM_e^o(p)$ are derived in direct analogy to (6).

Step 2: Convexity of $CM(\cdot)$ in p

We demonstrate the convexity of the aggregate annual contribution margin pointwise, that is, convexity holds at any point in time t. Specifically, it suffices to show that for any

$0 \leq \lambda \leq 1$:

$$\begin{aligned} CM(t|p_\lambda) &= A(t|p_\lambda) \cdot CF_h^*(t|p_\lambda) + B(t|p_\lambda) \cdot CF_e^*(t|p_\lambda) \\ &\leq \lambda \left[A(t|p^1) \cdot CF_h^*(t|p^1) + B(t|p^1) \cdot CF_e^*(t|p^1)\right] \\ &+ (1-\lambda) \left[A(t|p^0) \cdot CF_h^*(t|p^0) + B(t|p^0) \cdot CF_e^*(t|p^0)\right] \\ &= \lambda \cdot CM(t|p^1) + (1-\lambda) \cdot CM(t|p^o), \end{aligned} \tag{7}$$

where $p_\lambda \equiv \lambda \cdot p^1 + (1-\lambda) \cdot p^0$, $A(t|p) \equiv \eta_h \cdot p - q(t) - w_h$ and $B(t|p) \equiv q(t) - \frac{p}{\eta_e} - w_e$. As noted above, for any p, either $A(t|p) \leq 0$ or $B(t|p) \leq 0$ because $\eta_h \cdot \eta_e \leq 1$.

Suppose now, without loss of generality, that $A(t|p_\lambda) > 0$ in which case the left-hand side of the preceding inequality is equal to $A(t|p_\lambda)$. Finally, the right-hand side of the above inequality is given by:

$$\lambda \cdot \max\{A(t|p^1), B(t|p^1), 0\} + (1-\lambda) \cdot \max\{A(t|p^0), B(t|p^0), 0\}. \tag{8}$$

By construction, this last expression is at least as large as $\lambda \cdot A(t|p^1) + (1-\lambda) \cdot A(t|p^0)$, which, because of the linearity of $A(t|\cdot)$ in p, is equal to $A(t|p_\lambda)$, thus establishing the desired inequality. The claim regarding convexity of $CM(\cdot)$ then follows from the observation that the sum (integral) of convex functions is also convex.

Step 3: Net-Present Value of the Reversible PtG Systems

As in the previous steps, we focus on integrated reversible PtG systems, with the derivation for modular systems being entirely analogous. The levelized fixed cost of the reversible fuel cell, LFC, aggregates all fixed expenditures required over the life of the reversible PtG system. This aggregate expenditure is then divided by L, the levelization factor that expresses the discounted number of hours that the capacity is available over its lifetime. The resulting cost is then a unit cost per hour of operation. Formally:

$$LFC = f + \Delta \cdot c. \tag{9}$$

Here, f represents the levelized value of fixed operating costs, c represents the levelized capacity cost per kWh, and Δ captures the impact of income taxes and the depreciation tax shield. Denoting by v the system price of the reversible fuel cell per kW of peak electricity absorption and desorption, we have:

$$c = \frac{v}{L}, \tag{10}$$

with the levelization factor calculated as:

$$L = m \cdot \sum_{i=1}^{T} \gamma^i \cdot x^{i-1}.$$

Here m denotes the number of hours per year, that is, $m = 8,760$ and the parameter T represents the number of years of useful economic life of the system. Since capacity may degrade over time, we denote by x the degradation factor so that x^{i-1} gives the fraction of the initial capacity that is functioning in year i. The parameter $\gamma = (1+r)^{-1}$ and represents the discount factor with r as the cost of capital. This interest rate should be interpreted as the weighted average cost of capital if the levelized cost is to incorporate returns for both equity and debt investors[44].

Similarly, the levelized fixed operating cost per kWh similarly comprises the total discounted fixed operating cost incurred over the lifetime of the system.

$$f = \frac{\sum_{i=1}^{T} F_i \cdot \gamma^i}{L}. \tag{11}$$

The cost of capacity is affected by corporate income taxes through a debt and a depreciation tax shield, as interest payments on debt and depreciation charges reduce the taxable earnings of a firm. The debt tax shield is included in the calculation if r is interpreted as the weighted average cost of capital. Let d_i denote the allowable tax depreciation charge in year i. Since the assumed lifetime for tax purposes is usually shorter than the actual economic lifetime, we set $d_i = 0$ in those years. If α represents the effective corporate income tax rate, the tax factor is given by:

$$\Delta = \frac{1 - \alpha \cdot \sum_{i=1}^{T} d_i \cdot \gamma^i}{1 - \alpha}. \tag{12}$$

The formal claim then is that the net-present value of an investment in one kW of the integrated reversible PtG system is given by:

$$NPV = (1 - \alpha) \cdot L \cdot \big[CM(p) - LFC\big]. \tag{13}$$

This relation is readily verified by noting that the after-tax cash flows in year i is:

$$CFL_i(p) = x^{i-1} \cdot \int_0^m CM(t|p)\, dt - F_i - \alpha \cdot I_i(p), \tag{14}$$

where $I_i(p)$ denotes the taxable income in year i. Specifically:

$$I_i(p) = x^{i-1} \cdot \int_0^m CM(t|p)\, dt - F_i - v \cdot d_i. \tag{15}$$

Since $CFL_0 = -v$, the discounted value of all after-tax cash flows is indeed equal to the expression in (13). Similar reasoning yields that the unit net-present values of the modular PtG and GtP systems are, respectively, given by:

$$NPV_h = (1-\alpha) \cdot L \cdot \left[CM_h^o(p) - LFC_h^o\right],$$

and

$$NPV_e = (1-\alpha) \cdot L \cdot \left[CM_e^o(p) - LFC_e^o\right].$$

8 Data availability

The data used in this study are referenced in the main body of the paper and the Supplementary Information. Data that generated the plots in the paper are provided in the Supplementary Information. Additional data and information is available from the corresponding author upon reasonable request.

References

[1] Davis, S. J. *et al.* Net-zero emissions energy systems. *Science* **9793** (2018).

[2] Olauson, J. *et al.* Net load variability in the Nordic countries with a highly or fully renewable power system. *Nature Energy* **1**, 1–14 (2016).

[3] Arbabzadeh, M., Sioshansi, R., Johnson, J. X. & Keoleian, G. A. The role of energy storage in deep decarbonization of electricity production. *Nature Communications* **10** (2019).

[4] Braff, W. A., Mueller, J. M. & Trancik, J. E. Value of storage technologies for wind and solar energy. *Nature Climate Change* **6**, 964–969 (2016).

[5] Comello, S. & Reichelstein, S. The emergence of cost effective battery storage. *Nature Communications* **10**, 2038 (2019).

[6] De Luna, P. *et al.* What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science* **364** (2019).

[7] Staffell, I. *et al.* The role of hydrogen and fuel cells in the global energy system. *Energy and Environmental Science* **12**, 463–491 (2019).

[8] Preuster, P., Alekseev, A. & Wasserscheid, P. Hydrogen Storage Technologies for Future Energy Systems. *Annual Review of Chemical and Biomolecular Engineering* **8**, 445–471 (2017).

[9] Van Vuuren, D. P. *et al.* Alternative pathways to the 1.5C target reduce the need for negative emission technologies. *Nature Climate Change* **8**, 391–397 (2018).

[10] Parkinson, B., Balcombe, P., Speirs, J. F., Hawkes, A. D. & Hellgardt, K. Levelized cost of CO2 mitigation from hydrogen production routes. *Energy and Environmental Science* **12**, 19–40 (2019).

[11] Jacobson, M. Z. Energy modelling: Clean grids with current technology. *Nature Climate Change* **6**, 441–442 (2016).

[12] E.ON. E.ON and thyssenkrupp bring hydrogen production on the electricity market (2020). URL `https://bit.ly/3aSAM0r`.

[13] Hydrogen on the rise. *Nature Energy* **1**, 16127 (2016).

[14] Zakeri, B. & Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews* **42**, 569–596 (2015).

[15] Evans, A., Strezov, V. & Evans, T. J. Assessment of utility energy storage options for increased renewable energy penetration. *Renewable and Sustainable Energy Reviews* **16**, 4141–4147 (2012).

[16] Uniper SE. Siemens und Uniper bündeln Kräfte bei Dekarbonisierung der Stromerzeugung (2020). URL `https://www.uniper.energy/news/siemens-und-uniper-buendeln-kraefte-bei-dekarbonisierung-der-stromerzeugung/`.

[17] Guerra, O. J. *et al.* The value of seasonal energy storage technologies for the integration of wind and solar power. *Energy and Environmental Science* (2020).

[18] Guerra, O. J., Eichman, J., Kurtz, J. & Hodge, B. M. Cost Competitiveness of Electrolytic Hydrogen. *Joule* **3**, 2425–2443 (2019).

[19] Rau, G. H., Willauer, H. D. & Ren, Z. J. The global potential for converting renewable electricity to negative-CO2-emissions hydrogen. *Nature Climate Change* **8**, 621–626 (2018).

[20] IEA. The Future of Hydrogen. Tech. Rep. (2019).

[21] Elcogen. Reversible solid oxide cell technology as a power storing solution for renewable energy (Italy) (2018). URL `http://bit.ly/385mR4N`.

[22] Regmi, Y. N. *et al.* A low temperature unitized regenerative fuel cell realizing 60% round trip efficiency and 10 000 cycles of durability for energy storage applications. *Energy and Environmental Science* (2020).

[23] Ding, H. *et al.* Self-sustainable protonic ceramic electrochemical cells using a triple conducting electrode for hydrogen and power production. *Nature Communications* **11** (2020).

[24] Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I. The future cost of electrical energy storage based on experience rates. *Nature Energy* **6**, 17110 (2017).

[25] Proost, J. State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings. *International Journal of Hydrogen Energy* **44**, 4406–4413 (2019).

[26] Pellow, M. A., Emmott, C. J., Barnhart, C. J. & Benson, S. M. Hydrogen or batteries for grid storage? A net energy analysis. *Energy and Environmental Science* **8**, 1938–1952 (2015).

[27] Ferrero, D., Lanzini, A., Leone, P. & Santarelli, M. Reversible operation of solid oxide cells under electrolysis and fuel cell modes: Experimental study and model validation. *Chemical Engineering Journal* **274**, 143–155 (2015).

[28] Reichelstein, S. & Rohlfing-Bastian, A. Levelized Product Cost: Concept and decision relevance. *The Accounting Review* **90**, 1653–1682 (2015).

[29] MIT. The Future of Coal: Options for a Carbon-Constrained World. Tech. Rep. (2007).

[30] International Energy Agency. CO2 Emissions from Fuel Combustion 2017 - Highlights. Tech. Rep. (2017).

[31] Reuters. Texas power prices jump to record high as heat bakes state (2019). URL `https://reut.rs/2tw4h78`.

[32] Buttler, A. & Spliethoff, H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews* **82**, 2440–2454 (2018).

[33] Weidner, E., Ortiz Cebolla, R. & Davies, J. Global deployment of large capacity stationary fuel cells. Tech. Rep. (2019).

[34] Bundesrat. 383/19 Gesetz zur Änderung des Gesetzes über Energiedienstleistungen und andere Energieeffizienzmaßnahmen (2019). URL `https://www.bundesrat.de/bv.html?id=0383-19`.

[35] Glenk, G. & Reichelstein, S. Economics of Converting Renewable Power to Hydrogen. *Nature Energy* **4**, 216–222 (2019).

[36] Rivera-Tinoco, R., Schoots, K. & Van Der Zwaan, B. Learning curves for solid oxide fuel cells. *Energy Conversion and Management* **57**, 86–96 (2012).

[37] Wei, M., Smith, S. J. & Sohn, M. D. Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. *Applied Energy* **191**, 346–357 (2017).

[38] Saba, S. M., Müller, M., Robinius, M. & Stolten, D. The investment costs of electrolysis A comparison of cost studies from the past 30 years. *International Journal of Hydrogen Energy* **43**, 1209–1223 (2018).

[39] Ketterer, J. C. The impact of wind power generation on the electricity price in Germany. *Energy Economics* **44**, 270–280 (2014).

[40] Paraschiv, F., Erni, D. & Pietsch, R. The impact of renewable energies on EEX day-ahead electricity prices. *Energy Policy* **73**, 196–210 (2014).

[41] Wozabal, D., Graf, C. & Hirschmann, D. The effect of intermittent renewables on the electricity price variance. *OR Spectrum* **38**, 687–709 (2016).

[42] Kök, A. G., Shang, K. & Yücel, S. Impact of Electricity Pricing Policies on Renewable Energy Investments and Carbon Emissions. *Management Science* **64**, 131–148 (2018).

[43] Glenk, G. & Reichelstein, S. Synergistic Value in Vertically Integrated Power-to-Gas Energy Systems. *Production and Operations Management* **29**, 526–546 (2020).

[44] Ross, S. A., Westerfield, R. & Jordan, B. D. *Fundamentals of corporate finance* (Tata McGraw-Hill Education, 2008).

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10 Author contributions

G.G. initiated the research question and the techno-economic model. He also conducted the literature review, the data collection and the numerical calculations. The authors jointly analyzed the economic model and both contributed to the writing of the paper.

11 Competing interests

The authors declare no competing financial or non-financial interests.

Supplementary Information to
"Buffering the Volatility in Power Markets:
Reversible Power-to-Gas Systems"

Gunther Glenk, University of Mannheim and Massachusetts Institute of Technology,
Stefan Reichelstein, University of Mannheim and Stanford University

Supplementary Table 1. List of symbols and acronyms.

α	Effective corporate income tax rate	kW	Kilowatt
c	Cost of capacity per hour	kWh	Kilowatt hour
$CF(t)$	Capacity factor at time t	L	Levelization factor
CFL_i	After-tax cash flow in year i	LFC	Levelized fixed cost
$CM(t)$	Contribution margin at time t	m	Number of hours per year
Δ	Tax factor	$\mu(t)$	Deviation factor of prices
d_i	Allowable tax depreciation in year i	p	Hydrogen price
$\epsilon(t)$	Deviation factor of generation	PEM	Polymer electrolyte membrane
η_h	Conversion rate from electricity to hydrogen	PtG	Power-to-Gas
η_e	Conversion rate from hydrogen to electricity	$q(t)$	Electricity price at time t
f	Fixed operating cost per hour	r	Cost of capital
F_i	Fixed operating cost in year i	SOC	Solide oxide cell
γ	Discount factor	t	Hour within year i
Γ	Co-variation coefficient	T	Useful life of capacity investment
GtP	Gas-to-Power	v	System price of capacity
I_i	Taxable income in year i	w	Variable cost markup per kWh
kg	Kilogram	x	Annual degradation rate of capacity

Supplementary Table 2. Input variables for modular reversible Power-to-Gas.

Input Variable	Germany	Texas	Source
Electrolysis			
System price, v_h^o	1,606 €/kW	1,799 $/kW	Ref.[1]
Fixed operating cost, F_{hi}^o	48.18 €/kW	53.96 $/kW	Ref.[1]
Conversion rate to hydrogen, η_h^o	0.019 kg/kWh	0.019 kg/kWh	Ref.[1]
Gas Turbine			
System price, v_e^o	1,000 €/kW	1,199 $/kW	Ref.[2]
Fixed operating cost, F_{ei}^o	30.00 €/kW	33.60 $/kW	Ref.[2]
Conversion rate to electricity, η_e^o	20.00 kWh/kg	20.00 kWh/kg	Ref.[2]
Either subsystem			
Economic lifetime, T^o	25 years	25 years	Ref.[3]
Corporate income tax rate, α^o	30.00%	21.00%	German and U.S. Tax Code
Degradation rate, x^o	0.08%	0.08%	Ref.[4]
Depreciation rate, d_i^o	6.25% (16y linear)	100% Bonus	Ref.[5;6]
Cost of capital, r^o	4.00%	6.00%	Ref.[7;8]
Electricity market price (2019), q	3.77 €¢/kWh	3.77 $¢/kWh	`www.eex.com`; `www.ercot.com`
Cost markup for electricity generation, w_e^o	0.00 €¢/kWh	0.00 $¢/kWh	Hydrogen price includes supply
Cost markup for hydrogen generation, w_h^o	0.40 €¢/kWh	1.02 $¢/kWh	See Supplementary Table 4–5; conversion to $ with avg. exchange rate of 2019

Supplementary Table 3. Input variables for integrated reversible Power-to-Gas.

Input Variable	**Germany**	**Texas**	**Source**
System price, v	2,243 €/kW	2,512 \$/kW	Own review, see Methods
Fixed operating cost, F	67.29 €/kW	75.36 \$/kW	Own review, see Methods
Conversion rate to hydrogen, η_h	0.023 kg/kWh	0.023 kg/kWh	Ref.[2]
Conversion rate to electricity, η_e	20.00 kWh/kg	20.00 kWh/kg	Ref.[2]
Economic lifetime, T	15 years	15 years	Ref.[9]
Corporate income tax rate, α	30.00%	21.00%	German and U.S. Tax Code
Degradation rate, x	1.60%	1.60%	Ref.[10]
Depreciation rate, d_i	6.25% (16y linear)	100% Bonus	Ref.[5;6]
Cost of capital, r	4.00%	6.00%	Ref.[7;8]
Electricity market price (2019), q	3.77 €¢/kWh	3.77 \$¢/kWh	`www.eex.com`; `www.ercot.com`
Cost markup for electricity generation, w_e	0.00 €¢/kWh	0.00 \$¢/kWh	Hydrogen price includes supply
Cost markup for hydrogen generation, w_h	0.40 €¢/kWh	1.02 \$¢/kWh	See Supplementary Table 4–5; conversion to \$ with avg. exchange rate of 2019

Supplementary Table 4. Cost markup for hydrogen generation, Germany

Variable	**Value**	**Source**
Electricity price markup		
Transmission charge (€¢/kWh)	0.000	§118 (6) Energiewirtschaftsgesetz
Concession charge (€¢/kWh)	0.000	§118 (6) Energiewirtschaftsgesetz
EEG levy (€¢/kWh)	0.100	§64 (2) with A. 4 Erneuerbare-Energien-Gesetz
CHP levy (€¢/kWh)	0.030	§27 (1) Kraft-Wärme-Kopplungsgesetz
§19 StromNEV levy (€¢/kWh)	0.025	§19 (2) Stromnetzentgeltverordnung
Offshore liability levy (€¢/kWh)	0.030	§17f (5) Energiewirtschaftsgesetz
Levy for interruptable loads (€¢/kWh)	0.000	§18 Verordnung zu abschaltbaren Lasten
Electricity tax (€¢/kWh)	0.000	§9a (1) 1. Stromsteuergesetz
Total electricity price markup (€¢/kWh)	0.185	
Other variable cost		
Cost for water and other consumables (€/kg)	0.100	Estimation
Cost for water and other consumables (€¢/kWh)	0.210	Conversion with η_h
Total cost markup (€¢/kWh)	0.395	

Supplementary Table 5. Cost markup for hydrogen generation, Texas

Variable	Value	Source
Electricity price markup		
Transmission and distribution charges ($¢/kWh)	0.0077	Ref.[11], transmission rate
Transmission system charge ($¢/kWh)	0.3055	Ref.[11], transmission rate
Distribution system charge ($¢/kWh)	0.0668	Ref.[11], transmission rate
System benefit fund charge ($¢/kWh)	0.0000	Ref.[11], Rider SBF
Transition charge ($¢/kWh)	0.0000	Ref.[11], Schedules TC
Nuclear decommissioning charge ($¢/kWh)	0.0001	Ref.[11], Rider NDC
Transmission cost recovery factor ($¢/kWh)	0.3094	Ref.[11], Rider TCRF
Competition transition charge ($¢/kWh)	0.0000	Ref.[11], Rider CTC
Competitive metering credit ($¢/kWh)	0.0001	Ref.[11], Rider CMC
Other charges or credits ($¢/kWh)	0.0731	Ref.[11], Riders RCE, EECRF, DCRF
Griddy membership fee ($¢/kWh)	0.0001	Ref.[12]
Taxes ($¢/kWh)	0.0192	U.S. Tax Code
Total electricity price markup ($¢/kWh)	0.7880	
Other variable cost		
Cost for water and other consumables ($/kg)	0.1120	Conversion of € value to $ with avg. exchange rate of 2019
Cost for water and other consumables ($¢/kWh)	0.2356	Conversion with η_h
Total cost markup ($¢/kWh)	1.0236	

Supplementary Table 6. Current economics of modular reversible Power-to-Gas.

	Germany	Texas
Power-to-Gas Subsystem		
Contribution margin of hydrogen $CM_h^o(p_h^o)$	2.04 €¢/kWh	2.18 $¢/kWh
Break-even price for hydrogen, p_h^o	3.19 €/kg	2.86 $/kg
Capacity factor for hydrogen, $CF_h^o(p_h^o)$	0.95	0.93
Levelized fixed cost, LFC_h^o	2.03 €¢/kWh	2.17 $¢/kWh
Levelized fixed operating cost, f_h^o	0.60 €¢/kWh	0.67 $¢/kWh
Levelized capacity cost, c_h^o	1.28 €¢/kWh	1.74 $¢/kWh
Tax factor, Δ_h^o	1.12	0.86
Gas-to-Power Subsystem		
Contribution margin of electricity, $CM_e^o(p_e^o)$	1.28 €¢/kWh	1.35 $¢/kWh
Break-even price for hydrogen, p_e^o	0.54 €/kg	1.30 $/kg
Capacity factor for electricity, $CF_e^o(p_e^o)$	0.86	0.04
Levelized fixed cost, LFC_e^o	1.26 €¢/kWh	1.35 $¢/kWh
Levelized fixed operating cost, f_e^o	0.37 €¢/kWh	0.42 $¢/kWh
Levelized capacity cost, c_e^o	0.80 €¢/kWh	1.08 $¢/kWh
Tax factor, Δ_e^o	1.12	0.86

Supplementary Table 7. Current economics of integrated reversible Power-to-Gas.

	Germany	**Texas**
Upper Break-even Price		
Contribution margin of hydrogen $CM_h(p^*)$	3.75 €¢/kWh	2.62 \$¢/kWh
Break-even price for hydrogen, p^*	3.41 €/kg	2.59 \$/kg
Capacity factor for hydrogen, $CF_h(p^*)$	0.99	0.94
Contribution margin of electricity, $CM_e(p^*)$	0.00 €¢/kWh	1.17 \$¢/kWh
Capacity factor for electricity, $CF_e(p^*)$	0.00	0.02
Lower Break-even Price		
Contribution margin of hydrogen $CM_h(p_*)$	0.03 €¢/kWh	0.00 \$¢/kWh
Break-even price for hydrogen, p_*	0.02 €/kg	-0.01 \$/kg
Capacity factor for hydrogen, $CF_h(p_*)$	0.02	0.00
Contribution margin of electricity, $CM_e(p_*)$	3.71 €¢/kWh	3.82 \$¢/kWh
Capacity factor for electricity, $CF_e(p_*)$	0.97	1.00
Either Break-even Price		
Levelized fixed cost, LFC	3.73 €¢/kWh	3.79 \$¢/kWh
Levelized fixed operating cost, f	0.86 €¢/kWh	0.96 \$¢/kWh
Levelized capacity cost, c	2.58 €¢/kWh	3.29 \$¢/kWh
Tax factor, Δ	1.11	0.86

Supplementary Table 8. Prospects, Germany.

Year	v_h^o (€/kW)	η_h^o (kWh/kg)	p_h^o (€/kg)	p_e^o (€/kg)	v (€/kW)	η_h (kWh/kg)	η_e (kWh/kg)	p^* (€/kg)	p_* (€/kg)	$\bar{p}$ (€/kg)	$\underline{p}$ (€/kg)
2019	1,606	0.02	3.19	0.54	2243.00	0.02	20.00	3.41	0.02	2.43	-1.81
2020	1,530	0.02	3.09	0.54	2042.00	0.02	20.15	3.25	0.09	2.45	-1.82
2021	1,457	0.02	2.99	0.54	1859.00	0.02	20.30	3.11	0.15	2.47	-1.83
2022	1,387	0.02	2.90	0.54	1693.00	0.02	20.45	2.98	0.22	2.49	-1.85
2023	1,321	0.02	2.82	0.54	1541.00	0.02	20.61	2.86	0.27	2.51	-1.86
2024	1,258	0.02	2.74	0.54	1403.00	0.02	20.76	2.75	0.33	2.53	-1.87
2025	1,198	0.02	2.66	0.54	1278.00	0.02	20.91	2.65	0.38	2.54	-1.89
2026	1,141	0.02	2.58	0.54	1163.00	0.02	21.06	2.55	0.42	2.56	-1.90
2027	1,086	0.02	2.51	0.54	1059.00	0.02	21.21	2.47	0.47	2.58	-1.91
2028	1,035	0.02	2.44	0.54	964.00	0.02	21.36	2.39	0.51	2.60	-1.93
2029	985	0.02	2.38	0.54	878.00	0.02	21.52	2.31	0.55	2.62	-1.94
2030	938	0.02	2.32	0.54	799.00	0.02	21.67	2.24	0.59	2.64	-1.96

Supplementary Table 9. Prospects, Texas.

Year	v_h^o (\$/kW)	η_h^o (kWh/kg)	p_h^o (\$/kg)	p_e^o (\$/kg)	v (\$/kW)	η_h (kWh/kg)	η_e (kWh/kg)	p^* (\$/kg)	p_* (\$/kg)	$\bar{p}$ (\$/kg)	$\underline{p}$ (\$/kg)
2019	1,799	0.02	2.86	1.30	2512.00	0.02	20.00	2.59	-0.01	> 5.00	0.59
2020	1,713	0.02	2.76	1.30	2287.00	0.02	20.15	2.42	0.06	> 5.00	0.58
2021	1,631	0.02	2.67	1.30	2082.00	0.02	20.30	2.26	0.12	> 5.00	0.58
2022	1,553	0.02	2.58	1.30	1896.00	0.02	20.45	2.11	0.18	> 5.00	0.58
2023	1,479	0.02	2.49	1.30	1726.00	0.02	20.61	1.97	0.24	> 5.00	0.58
2024	1,409	0.02	2.41	1.30	1572.00	0.02	20.76	1.84	0.29	> 5.00	0.58
2025	1,342	0.02	2.34	1.30	1431.00	0.02	20.91	1.72	0.35	> 5.00	0.58
2026	1,278	0.02	2.27	1.30	1303.00	0.02	21.06	1.60	0.41	> 5.00	0.57
2027	1,217	0.02	2.20	1.30	1186.00	0.02	21.21	1.48	0.50	> 5.00	0.57
2028	1,159	0.02	2.13	1.30	1080.00	0.02	21.36	1.35	0.64	> 5.00	0.57
2029	1,103	0.02	2.07	1.30	983.00	0.02	21.52	1.16	0.91	> 5.00	0.57
2030	1,051	0.02	2.01	1.30	895.00	0.02	21.67	–	–	> 5.00	0.57

Supplementary References

[1] Glenk, G. & Reichelstein, S. Economics of Converting Renewable Power to Hydrogen. *Nature Energy* **4**, 216–222 (2019).

[2] IEA. The Future of Hydrogen. Tech. Rep. (2019).

[3] Michalski, J. *et al.* Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. *International Journal of Hydrogen Energy* **42**, 13427–13443 (2017).

[4] Buttler, A. & Spliethoff, H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews* **82**, 2440–2454 (2018).

[5] Bundesfinanzhof. BFH-Urteil 14.04.2011 IV R 52/10 (Bundesfinanzhof, 2011).

[6] U.S. Congress. H.R.1: An Act to provide for reconciliation pursuant to titles II and V of the concurrent resolution on the budget for fiscal year 2018. (2017).

[7] Fraunhofer ISI. The impact of risks in renewable energy investments and the role of smart policies. Tech. Rep. (2016).

[8] Moné, C., Stehly, T., Maples, B. & Settle, E. 2014 Cost of Wind Energy Review. Tech. Rep. February (2015).

[9] Elcogen. Solid Oxide Fuel Cells: Opportunities for a clean energy future. Tech. Rep. (2019).

[10] U.S. Department of Energy. Report on the Status of the Solid Oxide Fuel Cell Program. Tech. Rep. August (2019).

[11] CenterPoint Energy Houston Electric. Tariff for Retail Delivery Service (2020). URL `http://bit.ly/3820FJ0`.

[12] Griddy. Pricing (2020). URL `http://bit.ly/382npZk`.