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Market-based renewables: How flexible hydrogen electrolyzers stabilize wind and solar market values

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Abstract. Wind and solar energy are often expected to fall victim to their own success: the higher their share in electricity production, the more their revenue on electricity markets (their “market value”) declines. While in conventional power systems, the market value may converge to zero, this study demonstrates that “green” hydrogen production, through adding electricity demand in low-price hours, can effectively and permanently halt the decline. With an analytical derivation, a Monte Carlo simulation, and a numerical electricity market model, I find that – due to flexible hydrogen production – market values in 2050 likely converge above $\text{€}19 \pm 9 \text{ MWh}^{-1}$ for solar energy and above $\text{€}27 \pm 8 \text{ MWh}^{-1}$ for wind energy. This is in the range of the projected levelized costs of renewables and has profound implications. Market-based renewables may hence be within reach.

Keywords. Renewable energy, hydrogen electrolysis, electricity market, electricity economics, integrated energy system, flexible electricity demand.

Introduction

Variable renewables. Wind and solar energy play a key role in mitigating climate change¹. The share of these renewable energy sources in power generation has been increasing rapidly, a development sparked by policy support and amplified by cost reductions due to economies of scale and technological learning. Renewable energy sources can currently produce electricity at a levelized cost comparable to that of conventional technologies^{2,3}.

Value decline. Nevertheless, the full market integration of wind and solar energy may be challenging because of two distinct characteristics of these energy sources: their time-varying availability and their (near-)zero marginal cost. Hence, when they are available, their additional low-cost supply depresses electricity prices, leading to below-average market revenues^{4–12}. This “self-cannibalization” effect is substantial. At an assumed 30% market share, the market value of wind energy is estimated to decline by 20–50%⁶; the value of solar energy may decline even more¹⁰. As a result, it has often been thought that renewable investors cannot recover their costs on the market alone and that renewable support schemes will need to continue indefinitely^{6,13–17}.

Green hydrogen. Meanwhile, using renewable electricity in electrolyzers to produce hydrogen without the emission of carbon has recently become increasingly popular^{18,19}, and the investment cost of electrolyzers is expected to decrease^{20–22}. Not only could this “green” hydrogen substitute fossil fuels in non-electric applications, but also could a flexible operation of electrolyzers help the market

integration of variable renewables by absorbing wind and solar energy when and where it is abundant^{23,24}. Previous studies have investigated the competitiveness of green hydrogen versus hydrogen produced from fossil fuels^{20–22,25,26}, but electrolyzers have not yet been the focus of the literature on mitigating the decline in the value of renewable energy^{27–33}.

Contribution. In this study, I argue that electrolyzers can effectively halt the decline in the market value of renewables. This is because low wholesale electricity prices caused by renewables trigger merchant investment in electrolyzers, which produce hydrogen whenever electricity prices are low, and because the electrolyzers' additional electricity demand in turn stabilizes market prices and with them the value of renewables. Exploiting this mechanism, I derive an analytical formula for the minimum market value of renewables, I quantify this minimum market value for a wide range of parameters in a Monte Carlo analysis, and I validate the results with a numerical electricity market model. The results indicate that in 2050 electrolyzers will stabilize the value of solar energy above $\text{€}19 \pm 9 \text{ MWh}^{-1}$ and the market value of wind energy above $\text{€}27 \pm 8 \text{ MWh}^{-1}$. This finding is shown to be significant when compared to other options for mitigating the renewable value decline and when compared to recent estimates for the future costs of renewables. The variance in the estimates reflects uncertainty regarding the future hydrogen price and the future investment cost of hydrogen electrolyzers. I conclude that flexible electrolyzers and, more generally, flexible electricity demand are promising solutions for the integration of variable renewables, which should be considered when analyzing and regulating future electricity systems.

The economics of electrolyzers

Electricity economics. Standard frameworks in electricity economics, which have been used to study the market effect of renewables, traditionally take the electricity demand as given^{34,35}. This section further develops two of these frameworks, the merit order model and the price duration curve, to include demand-side dispatch and investment decisions for electrolyzers.

Merit order model. The merit order model holds that power generators are dispatched in the order of their marginal cost. Time-varying electricity prices emerge at the intersection of the resulting upward-sloping supply curve and the traditionally price-inelastic, vertical demand curve. In this model, renewables producing at zero marginal cost shift the supply curve outwards and hence depress prices – possibly even to zero³⁴ (Fig. 1a). Note that this article abstracts from negative prices induced by renewable support schemes³⁶.

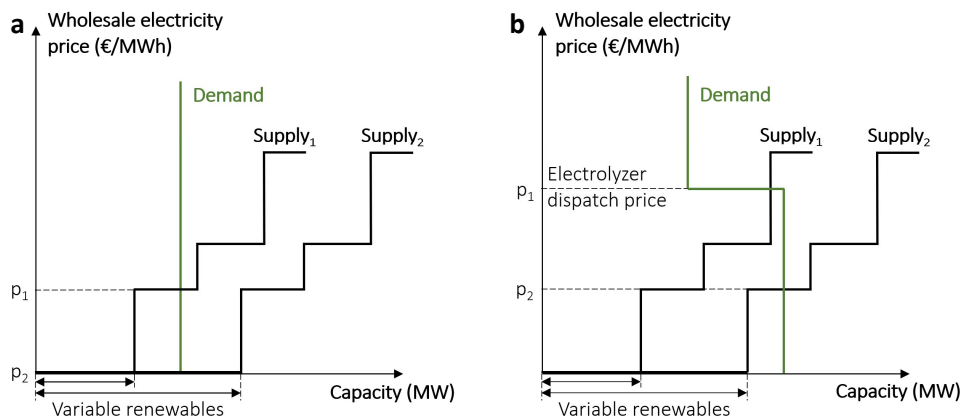


Figure 1: Merit order model with renewables and electrolyzers. Electricity prices p_1 and p_2 at two different times with varying supply from renewable sources. **a**, Without electrolyzers, the demand curve is vertical and electricity prices are relatively low (p_1) or even zero (p_2). **b**, With electrolyzers, their additional demand can increase (p_2) or even set (p_1) electricity prices.

Dispatch of electrolyzers. Electrolyzers start operating when electricity prices fall below their willingness to pay. This threshold, hereafter referred to as the electrolyzer dispatch price, $P_{dispatch}$, depends on the hydrogen price, P_{H_2} , the variable operational cost of electrolyzers, $C_{OPEX,var}$, the supplement that electrolyzers pay on top of the wholesale electricity price such as taxes or grid fees, C_{sup} , and on the electrolyzers' conversion efficiency, η :

$$P_{dispatch} = (P_{H_2} - C_{OPEX,var}) \cdot \eta - C_{sup} \quad (1)$$

Including hydrogen electrolyzers in the merit order price model yields higher demand below the dispatch price, which can increase or even set electricity prices (Fig. 1b). Note that this calculation assumes a time-invariant hydrogen price, justified by the low cost of hydrogen storage relative to electricity storage. This assumption will be relaxed later.

Price duration curve. The price duration curve allows analyzing investment decisions. It displays all electricity prices over one year in descending order. The price-depressing effect of renewables results in a downward-shifted price duration curve with a steeper slope (Fig. 2a).

Investment in electrolyzers. Merchant investment in electrolyzers will be made if their profit margin covers their fixed cost. The annual margin of electrolyzers is the difference between their dispatch price and the price duration curve. The annualized fixed cost of electrolyzers can be calculated as

$$AFC = \frac{i}{1-(1+i)^{-T}} \cdot C_{CAPEX} + C_{OPEX,fix}, \quad (2)$$

where C_{CAPEX} is the electrolyzers' investment cost, $C_{OPEX,fix}$ is their fixed operational cost, T is the systems' lifetime, and i is the interest rate.

Long-term equilibrium. Including hydrogen electrolyzers in the price duration curve limits the downward shift caused by renewables. If electricity prices fall so low that the annual margin of electrolyzers exceeds their annualized fixed cost, new electrolyzers will be installed, whose electricity demand stabilizes market prices. In the long term, an equilibrium arises that fulfills the zero-profit condition: the electrolyzers' annual margin equals their annualized fixed cost (Fig. 2b).

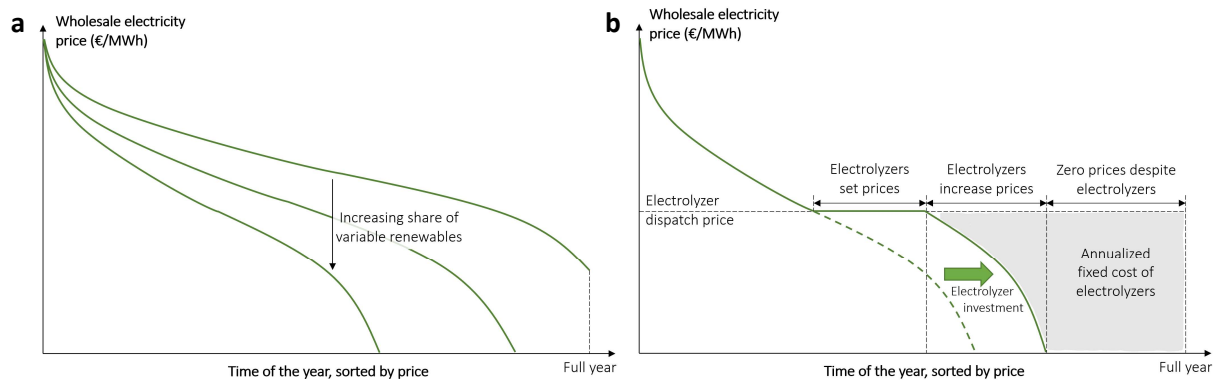


Figure 2: Price duration curves with renewables and electrolyzers. a, Renewables amplify the downward slope of the price duration curve. b, Through the additional electricity demand, merchant investment in electrolyzers increases or even sets electricity prices until the annual margin of electrolyzers equals their annualized fixed cost.

Analytical derivation

Outline. From the electrolyzers' zero-profit condition, this section derives an analytical formula for the minimum market value of renewables. Deriving this analytical *minimum* complements existing analytical expressions for the *decline* in the value of renewables^{11,12}. The derivation builds on two conservative assumptions (see Methods for a mathematical proof).

Maximum hours with zero prices. First, I assume that electricity prices are either zero or equal to the dispatch price of electrolyzers (Fig. 3a). Consequently, electrolyzers will earn a margin only when the electricity prices are zero, and the margin then equals their dispatch price. Using the zero-profit condition, the maximum number of hours with zero-prices, Z_{max} , can be estimated from the dispatch price, $P_{dispatch}$, and the annualized fixed cost, AFC , of electrolyzers:

$$Z_{max} = \frac{AFC}{P_{dispatch}} \quad (3)$$

This is an equilibrium condition: if the number of hours in which prices drop to zero exceeds Z_{max} , additional electrolyzer investments are profitable, reducing the number of zero price hours again.

Minimum market value. Second, I assume that the hours with a relatively high renewable production coincide with zero prices. Due to the first assumption, the remaining generation during hours without zero prices will then receive the electrolyzer dispatch price. Considering the ascending sorted hourly capacity factors of variable renewables over one year, $RE(t)$, as depicted in Fig. 3b, this assumption yields a conservative estimate for the market value of variable renewables, $value_{RE, min}$:

$$value_{RE, min} = \frac{\int_0^{8760-Z_{max}} RE(t) dt}{\int_0^{8760} RE(t) dt} \cdot P_{dispatch} \quad (4)$$

Alternative formulation. Eq. (4) can be rewritten to characterize the functional relationship between the minimum market value and flexible electrolyzers. Using the annual capacity factor of renewables, \overline{RE} , the average capacity factor during hours with zero prices, \overline{RE}_Z , and Eq. (3) yields

$$value_{RE, min} = \frac{8760 \cdot \overline{RE} - Z_{max} \cdot \overline{RE}_Z}{8760 \cdot \overline{RE}} \cdot P_{dispatch} = P_{dispatch} - \frac{\overline{RE}_Z}{8760} \cdot \frac{AFC}{\overline{RE}}. \quad (5)$$

By approximation, this implies that the minimum market value of renewables increases linearly with the electrolyzer dispatch price, and that it decreases with the ratio of the electrolyzers' annualized fixed cost and the renewables' annual capacity factor (neglecting changes in \overline{RE}_Z).

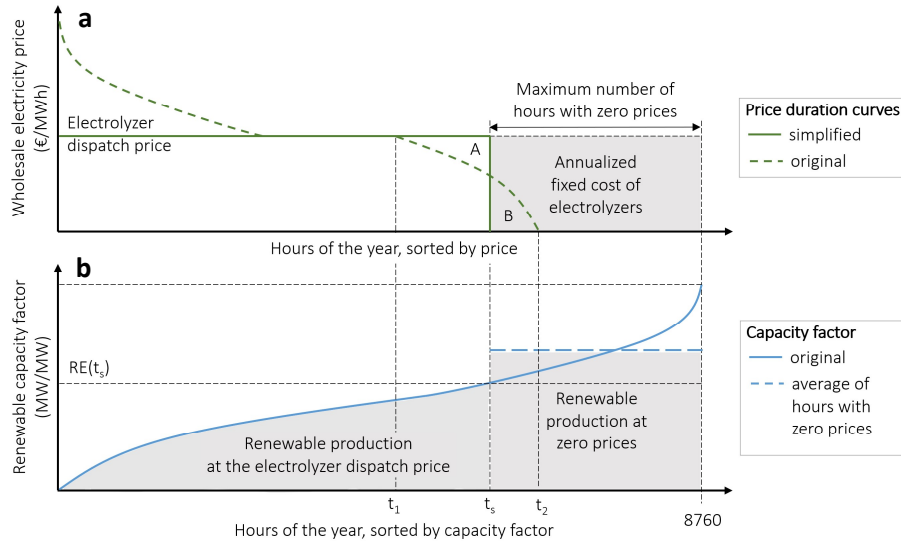


Figure 3: Estimating a lower boundary for the market value of renewables. **a**, Assuming that the electricity price is either zero or equal to the electrolyzers' dispatch price, the annualized fixed cost of electrolyzers defines a maximum number of hours with zero prices. **b**, Assuming that the highest production of variable renewables coincides with zero prices, the remaining production receives at least the electrolyzer dispatch price.

Monte Carlo simulations

Method and data. Based on the analytically derived minimum market value (Eq. (5)), this section quantifies this minimum for solar PV, wind onshore, and wind offshore in 2050. Monte Carlo simulations are performed to account for uncertainty. Hourly renewable generation profiles are randomly drawn from a large dataset covering 34 European countries and 10 different historic weather years³⁷, to calculate \overline{RE} and \overline{RE}_Z . For the other input parameters, I identify sensitivity ranges based on the most recent literature (Table 1), assuming a uniform distribution within these ranges. The supplement that electrolyzers pay on top of the wholesale electricity prices is initially set to zero and varied only in a subsequent sensitivity analysis.

Table 1: Parameter sensitivity ranges for the Monte Carlo simulations. CAPEX: capital expenditure, OPEX: operational expenditure.

Parameter	Unit	Sensitivity range	Source(s)
General			
Interest rate, i	%/a	4...10	
Hydrogen price, P_{H_2}	€/kg _{H2}	1.5...2.5	22,25
Hydrogen electrolyzers			
CAPEX, C_{CAPEX}	€/kW _{el}	100...800	20–22
Fixed OPEX, $C_{OPEX,fix}$	% of CAPEX	2	26
Variable OPEX, $C_{OPEX,var}$	€/kg _{H2}	0.1	25
Lifetime, T	a	20...30	25,26
Efficiency, η	kg _{H2} /MWh _{el}	20...22	22

The expected minimum market value. The Monte Carlo simulations reveal a significant magnitude of the hydrogen-induced minimum market value for all renewable technologies (Fig. 4). For solar PV, the simulations yield an expected value of €19 MWh⁻¹ with a standard deviation of €9 MWh⁻¹. The estimated minimum market value of wind onshore is somewhat higher and less uncertain (€27 ± 8 MWh⁻¹) because wind has a higher annual capacity factor than solar PV. These results are significant when compared to the projected levelized cost of €14-50 MWh⁻¹ for solar PV³⁸ and of €20-30 MWh⁻¹ for wind onshore³⁹. The estimates for wind onshore and offshore are similar, despite wind offshore having a substantially higher annual capacity factor. This is because the average capacity factor during hours with zero prices (\overline{RE}_Z) is also higher for wind offshore (see Eq. (5) and Supplementary Material, Fig. S1). The expected minimum market value for wind offshore, €28 MWh⁻¹, remains slightly below its projected levelized cost³⁹, €30-70 MWh⁻¹.

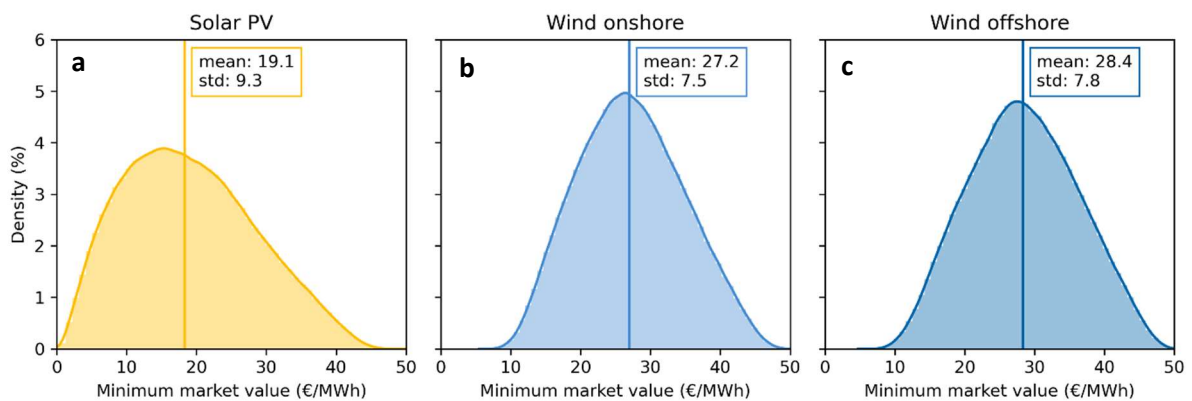


Figure 4: The expected minimum market value of renewables. a, Solar PV is characterized by a wide, right-skewed distribution. b, For wind onshore the distribution is more narrow and the mean is substantially higher, as compared to solar PV. c, Wind offshore features the highest mean, and the distribution is similar to wind onshore. The density functions are based on Monte Carlo simulations ($N = 1m$), vertical lines indicate the means of the distributions, and the confidence intervals (CI) are given in the boxes.

Sensitivity analyses. The substantial uncertainty involved with the minimum market value can be traced back to two hydrogen-related parameters, namely the price of hydrogen and the investment cost of electrolyzers (Fig. 5a, b). The hydrogen price, which is reflected in the electrolyzer dispatch price, increases the minimum market value almost linearly (approx. $\text{€}20 \text{ MWh}_{\text{el}}^{-1}$ per $\text{€}1 \text{ kg}_{\text{H}_2}^{-1}$). Different renewable energy sources are similarly affected, as expected based on Eq. (5). Lower investment cost of electrolyzers, which are reflected in the annualized fixed cost, have the potential to not only increase but also harmonize the minimum market value across different technologies (approx. $\text{€} 30\text{-}40 \text{ MWh}^{-1}$ at $\text{€}100 \text{ kW}_{\text{el}}^{-1}$). This illustrates how the impact of the electrolyzers' investment cost depends on the technology-specific capacity factors of renewables (Eq. (5)).

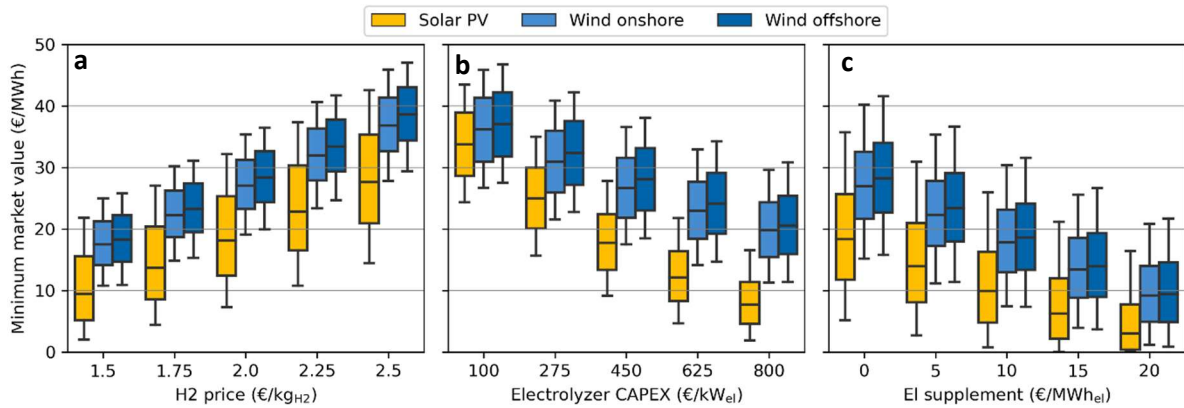


Figure 5: Major determinants of the minimum market value of renewables. **a**, The hydrogen (H_2) price drives up the minimum market value of all renewable technologies in a linear manner. **b**, Lower investment cost (CAPEX) of electrolyzers increase and harmonize the minimum market value of renewables across technologies. **c**, The supplement that electrolyzers pay on top of the wholesale electricity price depresses the market value of renewables. Each boxplot is based on Monte Carlo simulations ($N=100k$) with the hydrogen price, the electrolyzer investment cost, or the supplement being fixed to the value indicated on the x-axis. The black lines in the middle of the boxes indicate the median, the boxes extend from the first to the third quartile (inter-quartile range), and the whiskers include the 5-95% confidence interval of the observations.

Electricity price supplement. Further analyses reveal how sensitive the hydrogen-renewable relationship is to the supplement that electrolyzers pay on top of the wholesale electricity price (Fig. 5c). For every $\text{€}1 \text{ MWh}^{-1}$ increase in the supplement, the minimum market value of renewables decreases proportionally by about $\text{€}1 \text{ MWh}^{-1}$. The regulatory implications of this finding are derived in the Conclusions section.

Simplicity. The simplistic derivation and estimation of the minimum market value has strengths and limitations. Concerning strengths, this approach isolates and thereby helps to understand the pivotal role of the economics of hydrogen electrolyzers for the competitiveness of renewables. Furthermore, it is agnostic about many parameters of the power system, particularly about other electricity demand, supply, and storage. Hence, results can easily be generalized. The main limitation is that it estimates the *minimum* market value, not the market value itself. Other mitigation options for the decline in renewable market values^{27–33} can be expected to stabilize the market value above this lower boundary. At the same time, the assumption of a time-invariant hydrogen price may cause an overestimation of the minimum market value when compared to considering potential hydrogen price fluctuations. In addition, the transmission problem of both electricity and hydrogen is neglected, which may further aggravate this bias.

Electricity market modeling

Electricity market model. To address some of the above limitations, this section contrasts the simplistic estimates for the minimum market value with results from the more detailed electricity market model EMMA, which has been used for market value analyses before^{6,27,28} (see Methods for details). EMMA is applied here to calculate optimal investment, dispatch, and prices for the electricity market in the long-term partial equilibrium, as a response to exogenously fixed renewable capacity. While the results are reported for Germany only, four neighboring countries and corresponding cross-border trades are also modeled.

Scenarios. For this study, hydrogen electrolyzers with optimized dispatch and investment are introduced to the model, and the results are compared to those without electrolyzers. The parameters in Table 1 are now fixed to the center of the sensitivity ranges, including a hydrogen price of €2 kg_{H2}⁻¹ and an electrolyzer investment cost of €450 kW_{el}⁻¹. Three electrolyzer scenarios are compared:

1. The *H2 flex* scenario considers a constant hydrogen *price*, as assumed for the derivation of the minimum market value. This implies a perfectly flexible operation of electrolyzers.
2. The *H2 storage* scenario enforces a constant hydrogen *supply*, which may be required by some industrial processes. To still enable a flexible operation of electrolyzers, this scenario includes optimized hydrogen storage in salt caverns at investment cost of €2 kWh_{H2}⁻¹.
3. The *H2 inflex* scenario also enforces a constant hydrogen *supply*, but without hydrogen storage. This implies a perfectly inflexible operation of electrolyzers, which may result from regulatory incentives for steady electricity consumption.

Note that assuming a constant hydrogen supply implies that the hourly hydrogen price fluctuates, even though I fix the yearly base price to the same value as for the constant price scenario. Other key model inputs include a carbon price of €100 t_{CO2}⁻¹ and assumptions on electricity generators and storage, based on the long-term estimates from the European ASSET project⁴⁰. Further sensitivity runs are conducted with 50% higher and 50% lower values for electricity storage costs and carbon prices, respectively.

Impact of flexible electrolyzers. The results of the numerical model are in line with the analytical findings above: with electrolyzers, the market values of renewables converge; without electrolyzers, the market values continue to decline (Fig. 6).

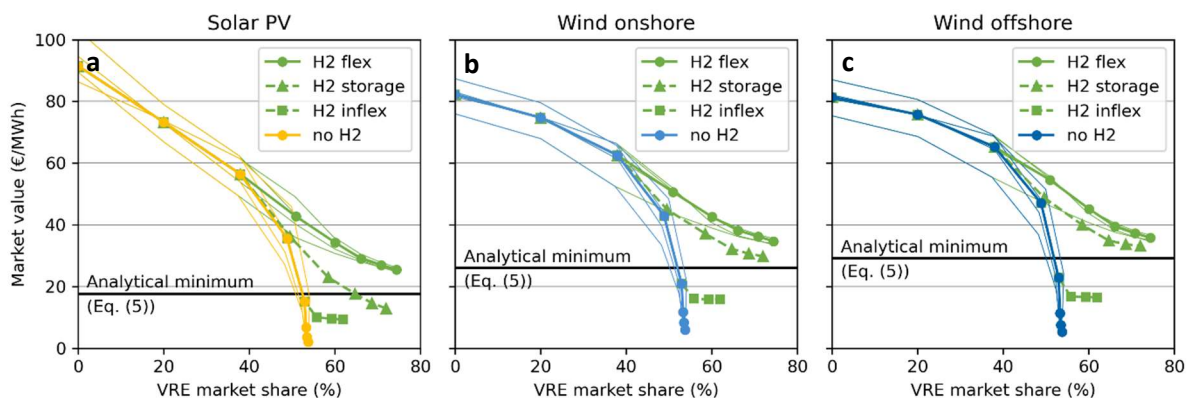


Figure 6: The impact of flexible electrolyzers on the market value of renewables. a, Solar PV, b, wind onshore, and c, wind offshore market values when these technologies are deployed simultaneously in equal shares. Market values with flexible electrolyzers (H2 flex) converge above the analytical minimum market value (Minimum); market values with electrolyzers that need storage for flexible operation (H2 storage) converge to somewhat lower values; market values with inflexible electrolyzers (H2 inflex) converge significantly lower; market values without electrolyzers (no H2) continue to decline. The main scenarios (dark colors) are contrasted with sensitivity runs with different electricity storage costs and carbon prices (light colors).

More precisely, in the *H2 flex* scenario, convergence occurs well above the analytical minimum (plus €7-9 MWh⁻¹). This is as expected because the minimum was proven a conservative estimate for the assumption of a constant hydrogen price. In the *H2 storage* scenario, the market values of wind and particularly solar decrease further, but they still seem to converge around the analytical minimum. This is plausible because, for the market value of renewables, the implications of considering an additional investment cost for hydrogen storage should be similar to those of an increase in the investment cost of electrolyzers (see Eq. (5) and Fig. 5b). In contrast, in the *H2 inflex* scenario, the market values converge substantially below the analytical minimum. This demonstrates the benefit of operating electrolyzers in a flexible manner. Remarkably, flexible electrolyzers (and to a lesser extent inflexible electrolyzers) also increase the market *share* of renewables, which means they disproportionately consume renewable electricity that would have been curtailed otherwise.

Other mitigation options. Further sensitivity scenarios highlight the importance of hydrogen electrolyzers relative to changes in the carbon price and in the cost of electricity storage (Fig. 6, light solid lines). While these other options for mitigating the decline in renewable market values have a distinct impact up to 50% renewables, they are negligible at higher renewable shares. For electricity storage, this is in line with Schill⁴¹, who highlights the growing importance of additional flexible electricity demand relative to electricity storage for the utilization of renewables at high market shares. The low sensitivity to CO₂ prices results from fossil generators switching to hydrogen, for which I assume a fixed price. In the absence of carbon capture and storage, however, CO₂ prices may drive up the price of hydrogen as a substitute for fossil fuels and thereby increase the market value of renewables, as demonstrated by Brown and Reichenberg³¹.

Characteristics of merchant electrolyzers. Finally, the market model provides further insights into the characteristics of merchant electrolyzers (Fig. 7). Their electricity consumption seems conceivable when compared to the electricity equivalent of the projected German hydrogen consumption in 2050¹⁹. The utilization of *flexible* electrolyzers is relatively low (20-45% in *H2 flex* and 40-55% in *H2 storage* scenario). This low utilization of flexible electrolyzers underlines the importance of low capital costs of hydrogen electrolyzers and hydrogen storage not only for the market value of renewables but also for total system costs, as discussed by Cloete et al.⁴².

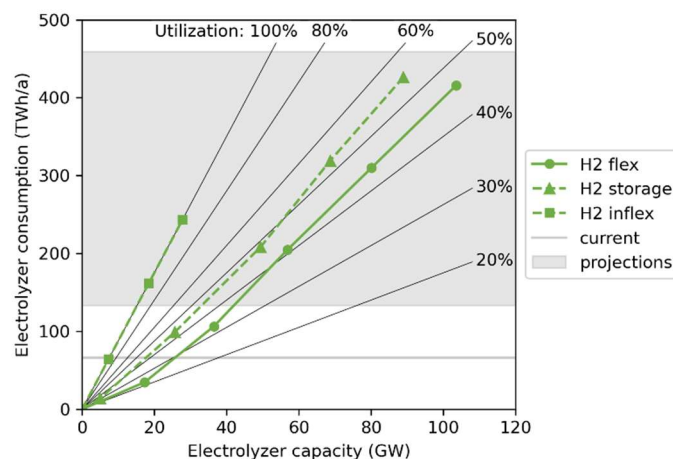


Figure 7: Details on flexible electrolyzers. Optimal electrolyzer capacity, consumption, and utilization for different shares of variable renewables. The results for the different electrolyzers scenarios (H2 flex, H2 storage, H2 inflex) are contrasted with the electricity equivalent of the current and projected hydrogen demand in Germany¹⁹.

Conclusions

Renewables-hydrogen synergy. This article demonstrates the strong synergy between variable renewables and flexible hydrogen production in wholesale electricity markets. Renewables can, by depressing market prices, trigger merchant investment in flexible electrolyzers, and these electrolyzers will, through their additional electricity demand, stabilize the market value of renewables. This finding has profound implications: by 2050, investment in renewables may be less in need of guaranteed state support than often thought. Put differently, flexible electrolyzers are a promising solution for the large-scale integration of renewables into the electricity system, and the simultaneous deployment of variable renewables and flexible electrolyzers appears beneficial from a public economic perspective.

Policy implications. Furthermore, this article illustrates how policy can facilitate the renewables-hydrogen synergy. First, politically defined supplements that electrolyzers pay on the wholesale electricity price are shown to reduce the market value of renewables. By contrast, exempting electrolyzers from electricity price supplements can help trigger investment in flexible electrolyzers and thereby increase both the market value and the market share of renewables. Hence, foregone supplement revenues can be worthwhile to reach higher renewable targets at lower cost of renewable support. Second, traditional regulation of electricity demand may incentivize *steady* electricity consumption, impeding both the market-based deployment of electrolyzers and synergy with renewables. Instead, regulation should support a *flexible* operation of electrolyzers, based on wholesale market prices.

Methodological contribution. Finally, this article highlights the importance of considering flexible demand when analyzing variable renewables. The presented framework for investment in and dispatch of flexible demand may be valuable beyond this article. One aspect which merits further investigation is the impact of sub-national grid restrictions, which would imply local variations in the value of electricity. Even though this article neglects such variations, its main analytical finding holds its generality: flexible electrolyzers can stabilize the value of renewables also locally, and the presented framework can be used to quantify the *local* minimum market value. Moreover, hydrogen production is only one example of flexible electricity demand, and the presented framework may be adapted to other applications, including electric heating, transport, and industry. Eventually, various types of flexible electricity demand will compete for using renewable electricity when electricity prices are low, jointly contributing to stabilizing the market value of renewables.

Methods

Outline. This section provides a mathematical proof of the minimum market value of renewables, and more detailed information on the electricity market model EMMA with hydrogen electrolyzers.

Mathematical proof of the minimum market value of renewables. The following is to prove mathematically that Eq. (4) is a lower boundary to the market value of renewable energy. To this end, consider the original price duration curve, $P(t)$, and let t_1 be the number of hours per year with electricity prices greater or equal to the electrolyzer dispatch price and let t_2 be the number of hours per year with above-zero electricity prices (Fig. 2a). Then, the zero-profit condition implies for the market equilibrium that:

$$AFC = \int_{t_1}^{t_2} (P_{dispatch} - P(t)) dt + \int_{t_2}^{8760} P_{dispatch} dt \quad (M1)$$

Now consider the simplified price duration curve resulting from the assumption that the electricity price is either zero or at least the electrolyzer dispatch price. Let $t_s = 8760 - Z_{max}$ be the number of hours with electricity prices equal or above the electrolyzer dispatch price under this assumption (Fig. 2a). The zero-profit condition still needs to be fulfilled, hence:

$$AFC = \int_{t_s}^{8760} P_{dispatch} dt \quad (M2)$$

Combining Eq. (M1) and Eq. (M2) yields:

$$\int_{t_1}^{t_s} (P_{dispatch} - P(t)) dt + \int_{t_s}^{t_2} (P_{dispatch} - P(t)) dt = \int_{t_s}^{t_2} P_{dispatch} dt \quad (M3)$$

This is equivalent to the following expression, which can be graphically interpreted as $A = B$ in Fig. 2a:

$$\int_{t_1}^{t_s} (P_{dispatch} - P(t)) dt = \int_{t_s}^{t_2} P(t) dt \quad (M4)$$

Now consider the definition of the market value of renewables for the original price duration curve:

$$\begin{aligned} value_{RE} &= \frac{1}{FLH_{RE}} \int_0^{8760} RE(t) \cdot P(t) dt \\ &= \frac{1}{FLH_{RE}} \left(\int_0^{t_1} RE(t) \cdot P(t) dt + \int_{t_1}^{t_2} RE(t) \cdot P(t) dt + \int_{t_2}^{8760} RE(t) \cdot P(t) dt \right) \end{aligned} \quad (M5)$$

For $t \leq t_1$, the original load duration curve exceeds the electrolyzer dispatch price, $P(t) \geq P_{dispatch}$, and for $t \geq t_2$, the original load duration curve is zero, $P(t) = 0$. Hence:

$$\begin{aligned} value_{RE} &\geq \frac{1}{FLH_{RE}} \left(\int_0^{t_1} RE(t) \cdot P_{dispatch} dt + \int_{t_1}^{t_2} RE(t) \cdot P(t) dt \right) \\ &= \frac{1}{FLH_{RE}} \left(\int_0^{t_1} RE(t) \cdot P_{dispatch} dt + \int_{t_1}^{t_s} RE(t) \cdot P(t) dt + \int_{t_s}^{t_2} RE(t) \cdot P(t) dt \right) \end{aligned} \quad (M6)$$

This can be rewritten as follows:

$$\begin{aligned} value_{RE} &\geq \frac{1}{FLH_{RE}} \left(\int_0^{t_1} RE(t) \cdot P_{dispatch} dt + \int_{t_1}^{t_s} RE(t) \cdot P_{dispatch} dt - \int_{t_1}^{t_s} RE(t) \cdot P_{dispatch} dt \right. \\ &\quad \left. + \int_{t_1}^{t_s} RE(t) \cdot P(t) dt + \int_{t_s}^{t_2} RE(t) \cdot P(t) dt \right) \\ &= \frac{1}{FLH_{RE}} \left(\int_0^{t_s} RE(t) \cdot P_{dispatch} dt - \int_{t_1}^{t_s} RE(t) \cdot (P_{dispatch} - P(t)) dt \right. \\ &\quad \left. + \int_{t_s}^{t_2} RE(t) \cdot P(t) dt \right) \end{aligned} \quad (M7)$$

The assumption that the highest production of variable renewables coincides with zero prices implies that $RE(t) \leq RE(t_s)$ for $t \leq t_s$ and $RE(t) \geq RE(t_s)$ for $t \geq t_s$ (Fig. 2b). Hence:

$$value_{RE} \geq \frac{1}{FLH_{RE}} \left(\int_0^{t_s} RE(t) \cdot P_{dispatch} dt - RE(t_s) \left(\int_{t_1}^{t_s} (P_{dispatch} - P(t)) dt - \int_{t_s}^{t_2} P(t) dt \right) \right) \quad (M8)$$

Using Eq. (M4) and $t_s = 8760 - Z_{max}$, this equation simplifies to:

$$value_{RE} \geq \frac{\int_0^{8760-Z_{max}} RE(t) dt}{FLH_{RE}} \cdot P_{dispatch} \quad (M9)$$

Hence, Eq. (4) is a lower boundary to the market value of renewable energy, which was to be proven.

The electricity market model EMMA. EMMA is a techno-economic model of the integrated Northwestern European electricity market, originally developed by Hirth⁴³. Technically, EMMA is a linear optimization model, minimizing the total cost of the electricity system. The main decision variables concern investment in and dispatch of electricity generation, storage, cross-country transmission, and – newly – hydrogen electrolyzers and storage. The investment and dispatch decisions as calculated by the model can hence be interpreted as economically efficient from a public economic perspective. Furthermore, the results reflect the partial

equilibrium of the electricity market with perfect competition. More precisely, as investment is optimized on the “green field” without considering existing power system assets, results can be interpreted as the *long-term* partial equilibrium. The corresponding power prices are read from the dual variables of the electricity balance constraint. This constraint, and hence power prices and dispatch decisions, feature an hourly resolution, while investment decisions are based on one entire year. The model is deterministic, that is all decisions are taken with perfect foresight. Regionally, the model covers Germany and four neighboring countries, namely France, Belgium, the Netherlands, and Poland. Reflecting zonal pricing in European electricity markets, grid congestion is modeled between countries, but not within the national bidding zones (“copperplate assumption”).

For this article, I included six renewable supply, five non-renewable supply, and two storage technologies in the model. Within the subset of renewables, the variable technologies wind onshore, wind offshore, and solar PV are included with exogenously fixed capacities. Corresponding profiles are taken from the METIS study³⁷ (as for the Monte Carlo analysis), selecting the weather year 2010. The other renewable technologies include hydro reservoir, hydro run-off-river, and bioenergy, of which the power generation fixed to 2018 levels because of resource constraints. I assume a constant temporal profile for bioenergy and seasonal profiles for the hydro inflow. The hydro reservoir usage is optimized by the model. The five non-renewable technologies comprise coal with carbon capture and storage (CCS), three types of combined cycle gas turbines, one fired with hydrogen and two fired with natural gas, either with or without CCS, and open cycle gas turbines, fired with natural gas. Dispatch of and investment in these technologies is freely optimized but for a minimum cogeneration capacity which needs to supply heat to district networks and industrial processes and is therefore limited in flexibility. No must-run for ancillary services is considered in this study, assuming that, by 2050, these can also be supplied by renewables and electricity storage. Electricity storage technologies include pumped hydro and batteries.

On the demand side of the electricity system, I newly introduced hydrogen electrolyzers and hydrogen storage with optimized investment and dispatch into the model. A hydrogen balance constraint links the hourly dispatch of hydrogen electrolyzers and storage to a time-invariant supply of hydrogen, for which the revenues are considered in the objective function. This setting represents the *H2 storage* scenario, in which storage investment is required to enable a flexible operation of electrolyzers. For the *H2 flex* scenario, the cost of hydrogen storage is set to zero, which results in a perfectly flexible operation of electrolyzers. For the *H2 inflex* scenario, hydrogen storage is excluded from the model to enforce a time-invariant dispatch of electrolyzers. In addition to the electricity consumption of hydrogen electrolyzers, the conventional electricity load is considered according to historic profiles from 2010 (same weather patterns as for the renewables). The annual conventional load is scaled to the average of 2016-2019. Load shedding is possible at costs of €1,000 MWh⁻¹.

In this study, the pre-curtailment electricity generation of variable renewables, $generation_{VRE}$, is exogenously scaled to values between zero to 140% of the yearly conventional load, $load_{conventional}$. This scaling affects wind onshore, wind offshore, and solar PV such that they equally contribute to the overall generation of variable renewables. The market share of variable renewables, $share_{VRE}$, is calculated post annual curtailment, $curtailment$, and considers the additional annual load from hydrogen electrolyzers, $load_{electrolyzers}$:

$$share_{VRE} = \frac{generation_{VRE} - curtailment}{load_{conventional} + load_{electrolyzers}} \quad (M10)$$

Note that this share of variable renewables excludes the non-variable renewable sources bioenergy and hydro, such that the overall share of renewables is higher.

Code availability

The code for the Monte Carlo simulations is available at <https://github.com/oruhnau/minimum-market-value>. The code for the electricity market modeling, including all model inputs and a full model description, is available at <https://github.com/emma-model/EMMA/tree/minimum-market-value>. Both repositories are published under an open-source license.

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Supplementary material to “Market-based renewables: How flexible hydrogen production stabilizes wind and solar market values”

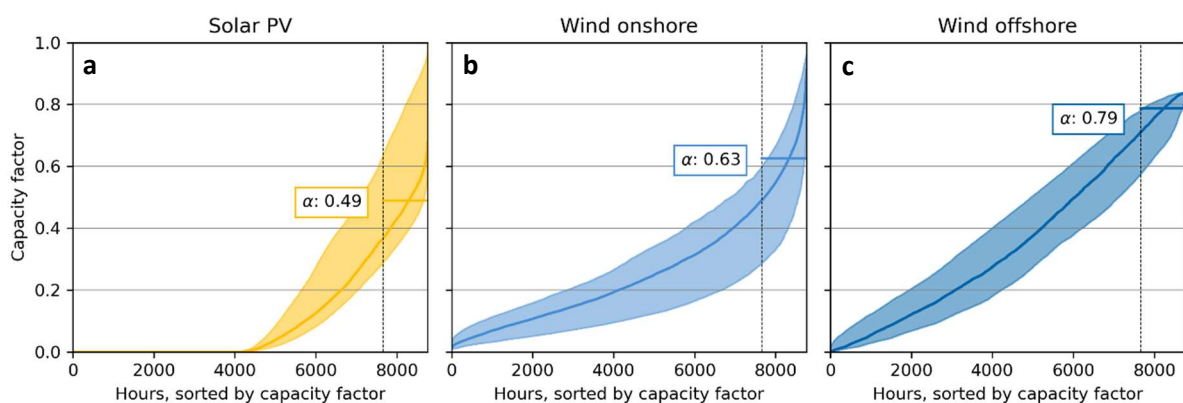


Figure S1: Hourly profiles of renewable capacity factors. a, Solar PV. b, Wind onshore. c, Wind offshore. The profiles are sorted in ascending order. The dark curve indicates the median and the light area the 5-95% quantile of all profiles. The horizontal lines indicate the average of the 1000 highest capacity factors (α for the example of $Z_{max} = 1,000$).