Decreasing market value of variable renewables can be avoided by policy action

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Traditional ‘primal’ view of market value of wind and solar

Prices are **depressed** by zero-marginal-cost wind and solar, which ‘**eat their own revenue**’. 
Traditional ‘primal’ view of market value of wind and solar

Market value, i.e. average price generator gets for feed-in, **declines with penetration.**

Source: Mills & Wiser (2014), Hirth (2013)
What the literature says about market value of wind and solar

- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
- “Variability is the fundamental cause of market value decline.”
- “Declining market value implies wind and solar become uneconomical at high shares.”
- “Market integration of large shares of variable renewables is impossible.”
- “New low-carbon technologies will be necessary at high penetrations.”

Source: Diverse energy economics literature.
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We show that from a dual perspective, each of these statements is wrong.
Market value decline depends on market structure

Implicit assumption in literature: VRE are forced in with subsidies or quotas, pushing MV down. However, if VRE are drawn in with CO$_2$ pricing, MV does not decline.

Source: Brown & Reichenberg (2021)
This holds even up to 100% wind and solar...

...provided there is **flexibility** from long- and short-term storage and/or transmission expansion.

Source: Brown & Reichenberg (2021)
Example from primal perspective: solar support versus CO₂ pricing

Source: Brown & Reichenberg (2021)
Market value in a perfect equilibrium: zero profit

In a long-term equilibrium, capacities of generators $G_s$ maximise economic welfare:

$$
\max_{d_{a,t}, g_{s,t}, G_s} \left[ \sum_{a,t} U_{a,t}(d_{a,t}) - \sum_s c_s G_s - \sum_{s,t} o_s g_{s,t} \right]
$$

where the demands $d_{a,t}$ are met in every hour $t$ by the generation dispatch $g_{s,t}$:

$$
\sum_a d_{a,t} - \sum_s g_{s,t} = 0 \perp \lambda_t
$$

Every generator $s$ makes backs its long-run costs, the zero-profit rule (Boiteaux, 1949).

$\Rightarrow$ Per MWh, levelised cost of electricity (LCOE) and market value (MV) are identical:

$$
LCOE_s \equiv \frac{c_s G_s + \sum_t o_s g_{s,t}}{\sum_t g_{s,t}} = \frac{\sum_t \lambda_t g_{s,t}}{\sum_t g_{s,t}} \equiv MV_s
$$
Market value decline: ‘dual’ mechanism with support policy

Altering the equilibrium requires policy. Forcing in a share of generators \( s \in S \) depresses their market value by the constraint's shadow price \( \mu_S \), a Feed-in Premium (FiP) for \( s \in S \):

\[
\sum_{s \in S} g_{s,t} \geq \Gamma \perp \mu_S \Rightarrow MV_s = LCOE_s - \mu_S
\]

From dual perspective, forcing in generators and sinking market value are two sides of same coin.

Cannot have one without the other.

This statement is technology-neutral, no (direct) relation to variability.

Source: Brown & Reichenberg (2021)
Market value decline: demonstration with support policy

In a stylised power model, this behaviour can be reproduced for Feed-in Premium (FiP) $\mu_S$:

$$\sum_{s \in S} g_{s,t} \geq \Gamma \perp \mu_S \Rightarrow MV_s = LCOE_s - \mu_S$$

Model detail:

- Model adapted from *Hirth (2013)*
- Germany + neighbouring countries
- Electricity only
- Wind, solar, fossil gas, coal, lignite
- Long-term equilibrium
- Energy-only model
- Hourly for representative year

Source: *Brown & Reichenberg (2021)*
Market value decline: primal versus dual perspective

**Primal perspective:**
- Market value declines because zero-marginal-cost VRE pushes out other generators
- Variability is the fundamental cause
- Only affects wind and solar generators

**Dual perspective:**
- Market value declines because share of generation is forced beyond equilibrium
- Policy is the fundamental cause
- Affects all generators which are forced beyond equilibrium
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Perspectives and framing have consequences!
Market value penetration with CO₂ pricing

If we draw in VRE by constraining CO₂ emissions, then only the market values of fossil generators with specific emissions \(e_s\) are affected by the **carbon shadow price** \(\mu_C\):

\[
\sum_{s,t} e_s g_{s,t} \leq K \quad \parallel \quad \mu_C \quad \Rightarrow \quad MV_s = LCOE_s + e_s \mu_C
\]

Source: Brown & Reichenberg (2021)
With VRE as the only low-C generators, system costs **barely differ** between policies.

⇒ MV collapse under support policy does not necessarily indicate system is pathological.

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**Source:** Brown & Reichenberg (2021)
Role of flexibility

Flexibility only **delays** market value decline for support policies.

For CO\(_2\) policies it **stabilises** LCOE = MV above penetrations of 70%.

Flexibility added here:

- short-term storage (batteries)
- long-term storage (hydrogen)
- transmission expansion

Source: Brown & Reichenberg (2021)
Support policy for nuclear shows similar results

Nuclear revenue is also suppressed under a support policy, declining to zero at high penetrations because of the variable demand. A CO$_2$ price avoids this behaviour.

\[\Rightarrow\] Nothing specific to VRE about MV suppression.

\[\Rightarrow\] Policy is responsible for MV decline, variability only affects the speed.

Source: Brown & Reichenberg (2021)
In breakdown of system costs, hydrogen storage balances the system at high penetrations.
Price duration curves under a CO\(_2\) policy

CO\(_2\) price raises prices when fossil generators on margin, but also storage bids high opportunity costs when discharging, while charging bids reduce hours when prices are zero.

⇒ Market does not degenerate into bifurcation of prices between zero and very high.

Source: Brown & Reichenberg (2021)
The distribution of hours when VRE earns its money barely changes as CO$_2$ emission reduce.

$\Rightarrow$ VRE does not become dependent on only a small number of hours to make money.
What we say about market value of wind and solar

- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
  - **No**, if drawn in with a CO\(_2\) price, market value does not decline.

- “Variability is the fundamental cause of market value decline.”
  - **No**, policy is the fundamental cause (no policy, no decline), but variability affects speed.

- “Declining market value implies wind and solar become uneconomical at high shares.”
  - **Not necessarily**: market value can decline even when system cost is close to optimal.

- “Market integration of large shares of variable renewables is impossible.”
  - **No**, wind and solar can be integrated into markets with sufficient flexibility.

- “New low-carbon technologies will be necessary at high penetrations.”
  - **Not necessarily**, but they may help to reduce system costs.
Conclusions

- From a **dual perspective**, market value decline is **guaranteed** if generators pushed in with subsidy/quotas

- Can construct reasonable market designs with CO₂ pricing that show **no market value decline** as the penetration for wind and solar rises (even up to 100%)

- To preserve market value of wind and solar, choose to **value their low emissions**

- In markets that rely on subsidies alone, market value decline **does not necessarily indicate problems** (i.e. can still be close to system optimum for CO₂ reduction)

- Can **combine** CO₂ pricing with support to maintain market value & reduce investor risk

- Given its policy-dependence, **use market value with caution** (like LCOE) & **focus on system cost** instead

Further reading: Brown & Reichenberg, “Decreasing market value of variable renewables can be avoided by policy action,” Energy Economics (2021), [doi:10.1016/j.eneco.2021.105354](https://doi.org/10.1016/j.eneco.2021.105354).
Before 2016 market value declines with rising subsidies; after 2016 it rises as CO₂ prices rise.

Source: Brown & Reichenberg (2021)
System cost as a function of CO$_2$ emissions

Without flexibility:

![Graph showing system cost as a function of CO$_2$ emissions]

- VRE support policy
- CO$_2$ policy

Source: Brown & Reichenberg (2021)
Relative market value (RMV) / value factor

With and without flexibility:

Source: Brown & Reichenberg (2021)
Pan-European model with heating and transport behaves similarly

Relative market value (market value divided by average market price) in PyPSA-Eur-Sec:

Source: Brown et al, 2019
| Quantity               | Unit       | EMMA | PyPSA |
|------------------------|------------|------|-------|
| lignite cost           | €/kW       | 2200 | 2200  |
| lignite fuel cost      | €/MWh_{th} | 3    | 3     |
| lignite+CCS cost       | €/kW       | 3500 | n/a   |
| lignite+CCS fuel cost  | €/MWh_{th} | 3    | n/a   |
| coal cost              | €/kW       | 1500 | 1500  |
| coal fuel cost         | €/MWh_{th} | 11.5 | 11.5  |
| CCGT cost              | €/kW       | 1000 | 1000  |
| CCGT fuel cost         | €/MWh_{th} | 25   | 25    |
| OCGT cost              | €/kW       | 600  | 600   |
| OCGT fuel cost         | €/MWh_{th} | 50   | 50    |
| load shedding cost     | €/MWh_{el} | 1000 | 1000  |

Table 1: Comparison of technology assumptions in the different models.

Source: Brown et al, 2019
## Cost assumptions 2/2

| Quantity                  | Unit                  | EMMA  | PyPSA  |
|---------------------------|-----------------------|-------|--------|
| wind cost                 | €/kW                  | 1300  | 1040   |
| solar cost                | €/kW                  | 2000  | 510    |
| nuclear cost              | €/kW                  | 4000  | 6000   |
| nuclear fuel cost         | €/MWh$_{th}$          | 3     | 3      |
| battery inverter          | €/kW                  | n/a   | 333    |
| battery storage           | €/kWh                 | n/a   | 167    |
| H$_2$ electrolysis        | €/kW$_{el}$           | n/a   | 750    |
| H$_2$ electrolysis efficiency | %                  | n/a   | 80     |
| H$_2$ turbine             | €/kW$_{el}$           | n/a   | 800    |
| H$_2$ storage             | €/kWh                 | n/a   | 0.5    |
| transmission expansion    | €/(MWkm)              | n/a   | 400    |

**Table 2:** Comparison of technology assumptions in the different models. 

Source: *Brown et al, 2019*
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