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

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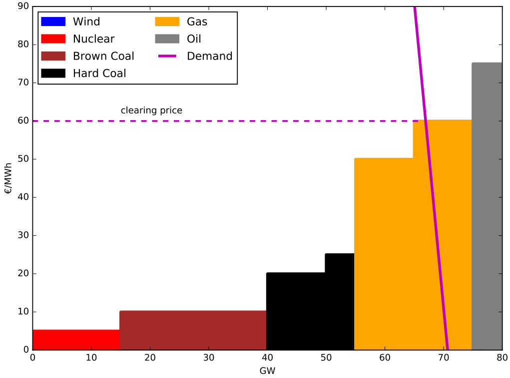
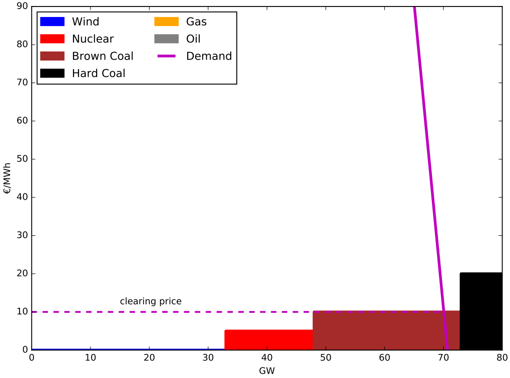
Traditional 'primal' view of market value of wind and solar

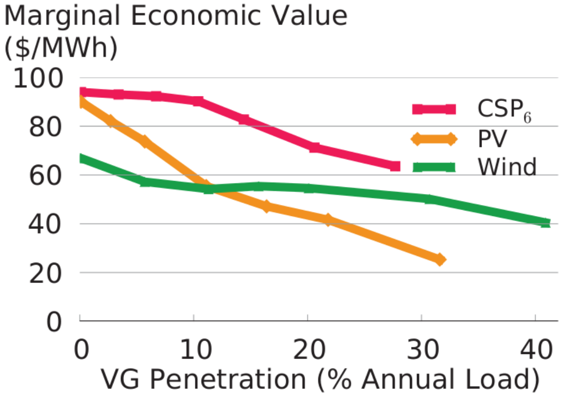
Prices are **depressed** by zero-marginal-cost wind and solar, which **'eat their own revenue'**.

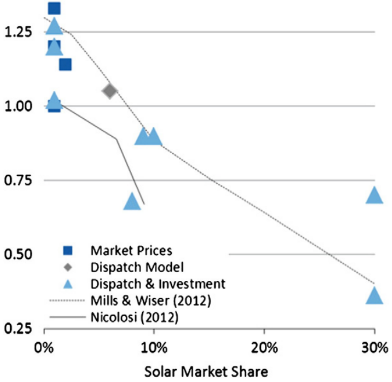




Traditional ‘primal’ view of market value of wind and solar

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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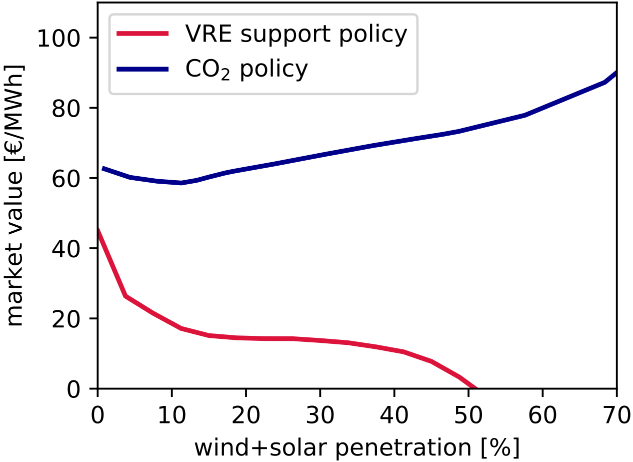
We show that from a **dual perspective**, each of these statements is **wrong**.

Source: Diverse energy economics literature.

Market value decline depends on market structure

Implicit assumption in literature: VRE are forced in with subsidies or quotas, pushing MV down.

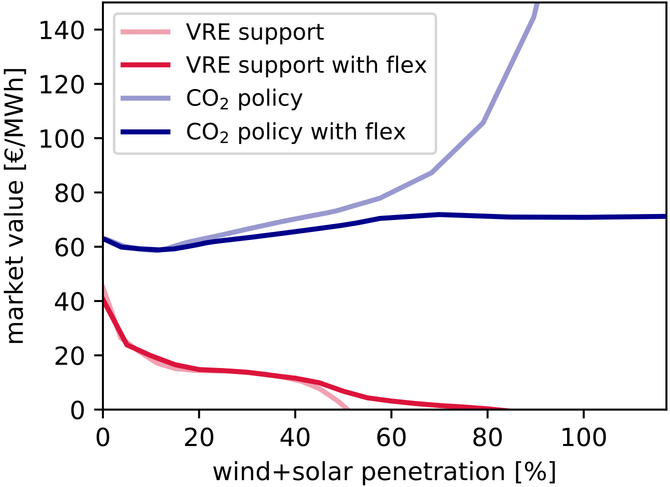
However, if VRE are drawn in with CO_2 pricing, MV does not decline.



Source: Brown & Reichenberg (2021)

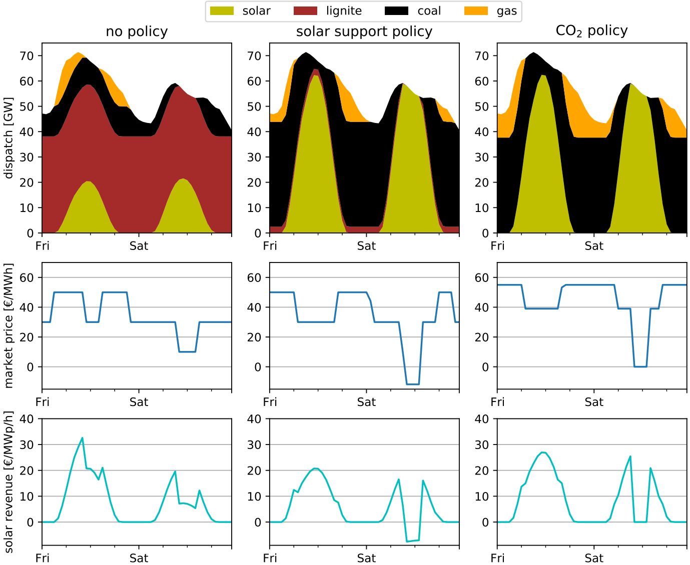
This holds even up to 100% wind and solar...

...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 CO_2 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 $g_{s,t}$:

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

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

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

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

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

Cannot have one without the other.

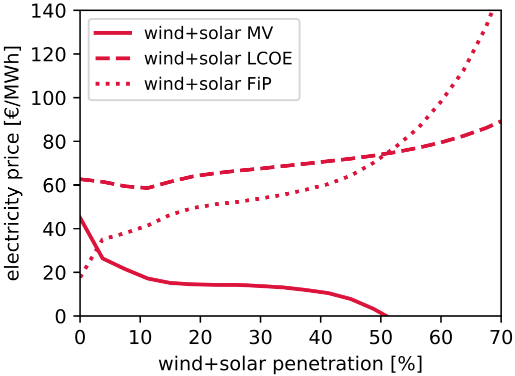
This statement is **technology-neutral**, no (direct) relation to variability.

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) μ_S:

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



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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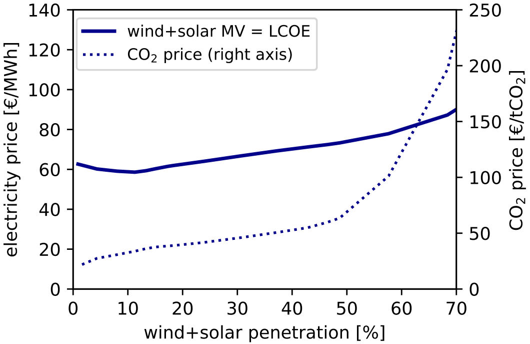
Perspectives and framing have consequences!

Market value penetration with CO_2 pricing

If we draw in VRE by constraining CO_2 emissions, then only the market values of fossil generators with specific emissions e_s are affected by the **carbon shadow price** μ_C:

$$\sum_{s,t} e_s g_{s,t} \leq K \quad \perp \quad \mu_C \qquad \Rightarrow \qquad MV_s = LCOE_s + e_s \mu_C$$

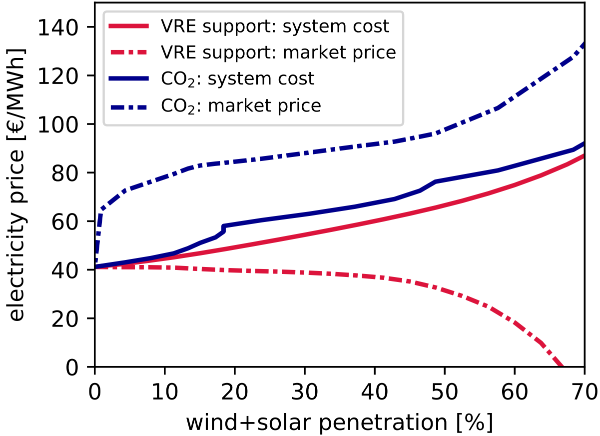


Source: **Brown & Reichenberg (2021)**

System cost

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.

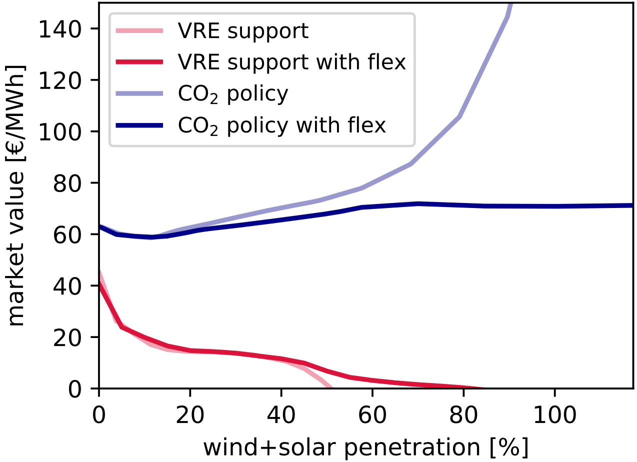


Source: Brown & Reichenberg (2021)

Role of flexibility

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

For CO_2 policies it **stabilises** LCOE = MV above penetrations of 70%.



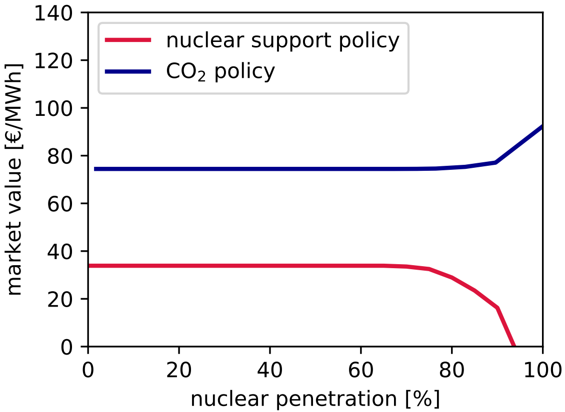
Flexibility added here:

- 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.



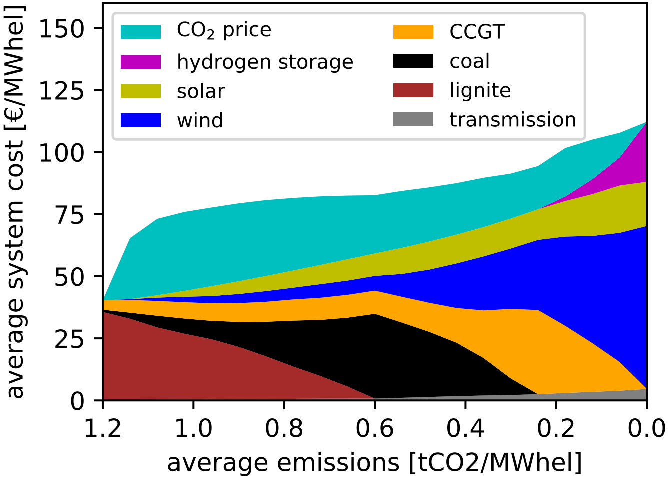
⇒ **Nothing specific to VRE about MV suppression**.

⇒ **Policy is responsible for MV decline**, variability only affects the speed.

Source: **Brown & Reichenberg (2021)**

System costs for CO_2 policy

In breakdown of system costs, hydrogen storage balances the system at high penetrations.



Source: Brown & Reichenberg (2021)

Price duration curves under a CO_2 policy

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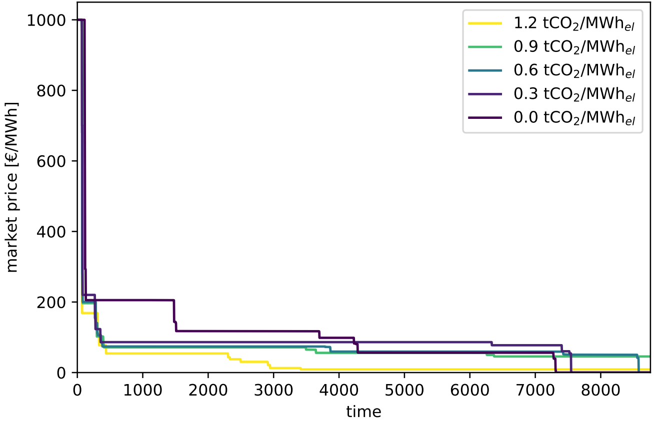
CO_2 price raises prices when fossil generators on margin, but also storage bids **high opportunity costs** when discharging, while charging bids reduce hours when prices are zero.

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



Source: Brown & Reichenberg (2021)

Average revenue per capacity per hour

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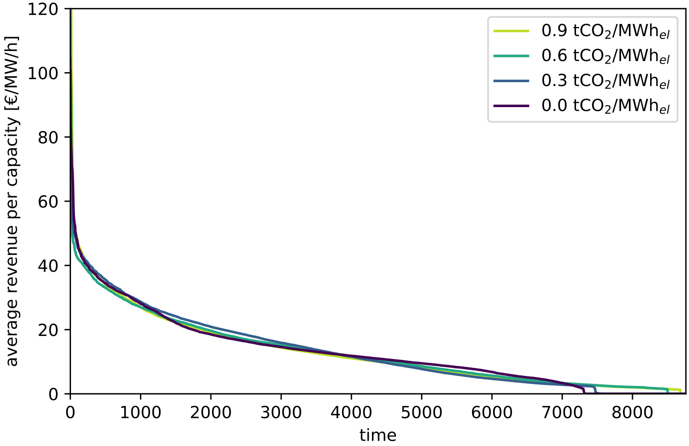
The distribution of hours when VRE earns its money barely changes as CO_2 emission reduce.

⇒ 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

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- "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

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- From a **dual perspective**, market value decline is **guaranteed** if generators pushed in with subsidy/quotas
- Can construct reasonable market designs with CO_2 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 CO_2 reduction)
- Can **combine** CO_2 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.

Real German data

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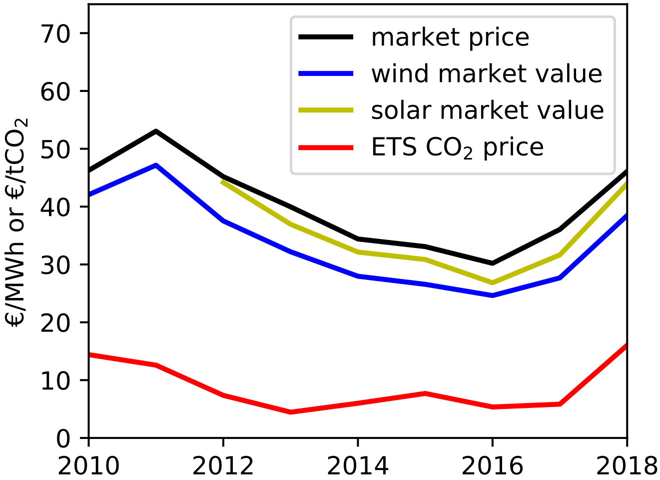
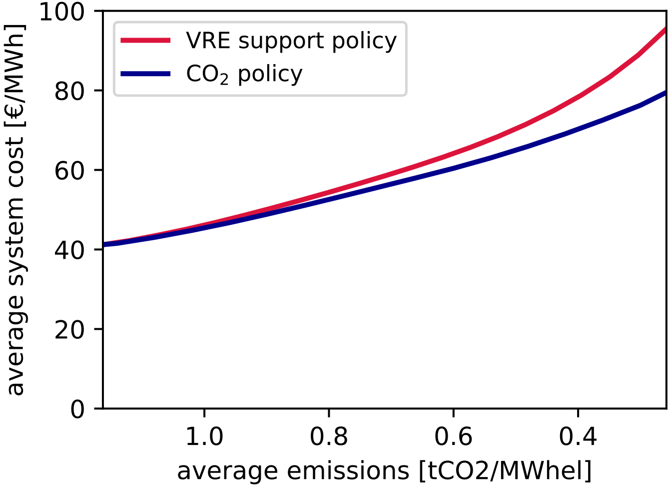
Before 2016 market value declines with rising subsidies; after 2016 it rises as CO_2 prices rise.



Source: Brown & Reichenberg (2021)

System cost as a function of CO_2 emissions

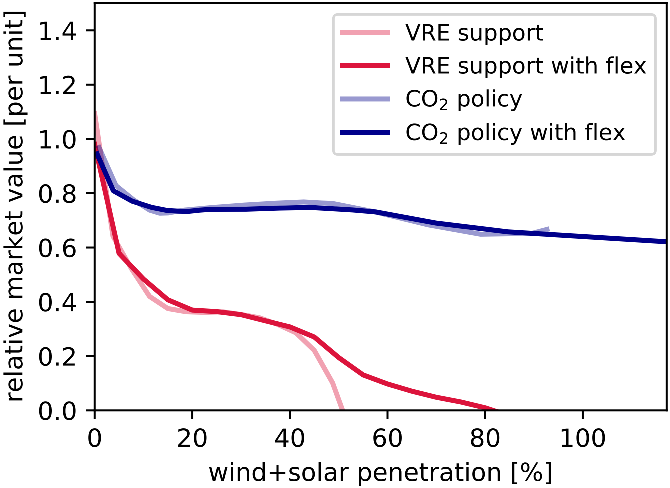
Without flexibility:



Source: **Brown & Reichenberg (2021)**

Relative market value (RMV) / value factor

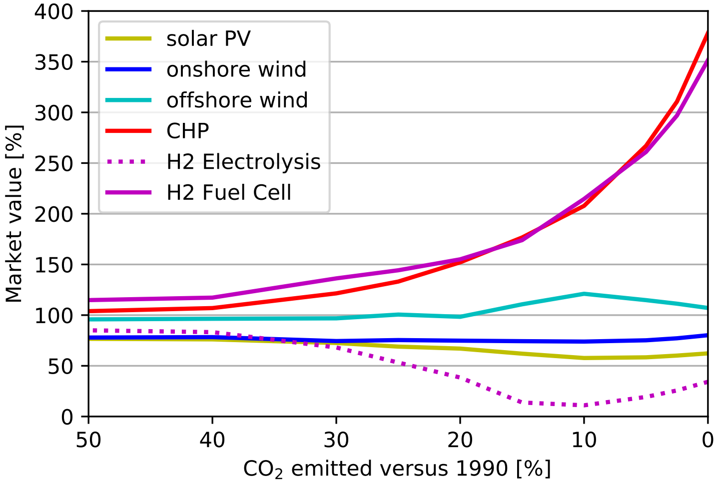
With and without flexibility:



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**

Cost assumptions 1/2

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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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