

Energy Economics, Winter Semester 2025-6

Lecture 13: The Future

Prof. Tom Brown, Philipp Glaum

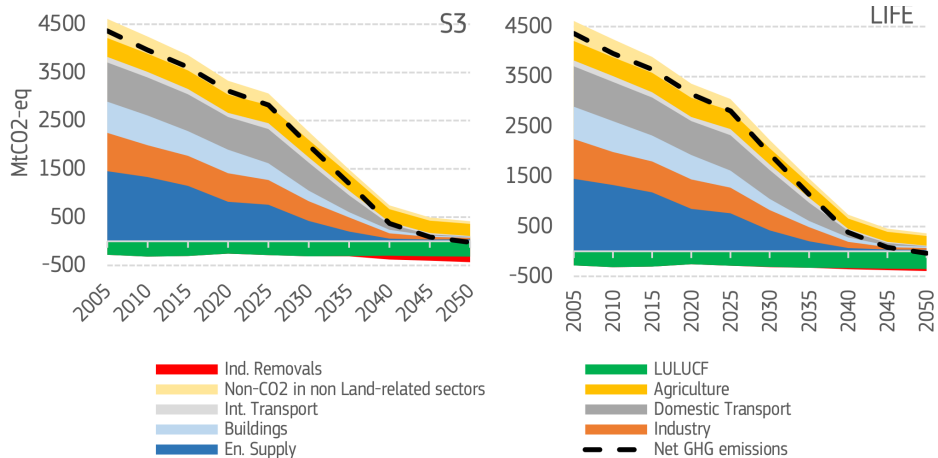
[Department of Digital Transformation in Energy Systems](#), Institute of Energy Technology, TU Berlin

Unless otherwise stated, graphics and text are Copyright ©Tom Brown, 2021-5. Graphics and text for which no other attribution are given are licensed under a Creative Commons Attribution 4.0 International Licence. 

Possible Pathways

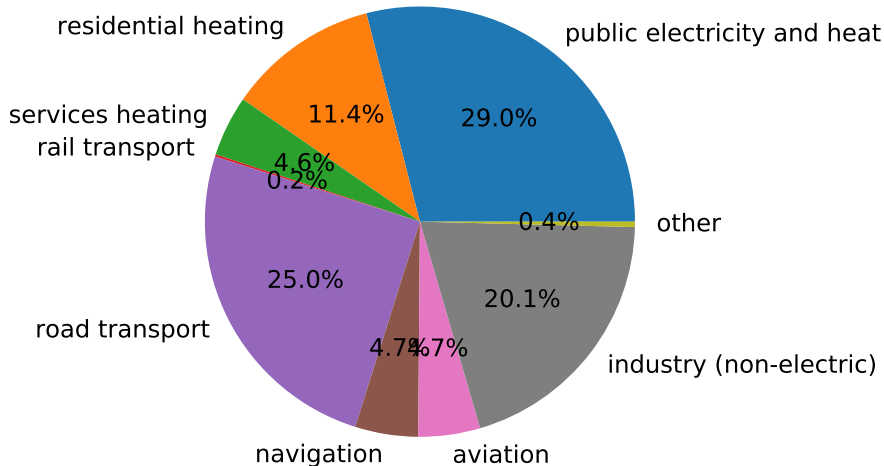
The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

Paris-compliant 1.5° C scenarios from European Commission for **net-zero GHG in EU by 2050**. This target has been adopted by the EU and enshrined in the **European Green Deal**.



It's not just about electricity demand...

EU28 CO₂ emissions in 2016 (total 3.5 Gt CO₂, 9.7% of global):



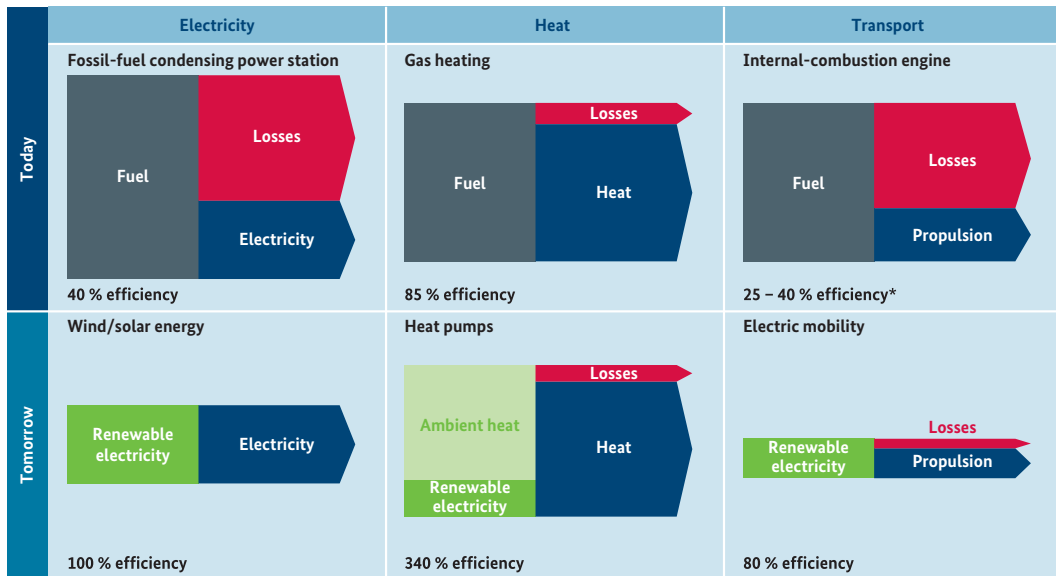
...but electrification of other sectors is critical for decarbonisation

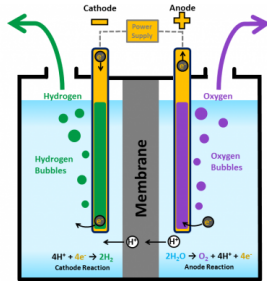
Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

Some scenarios show a **doubling or more of electricity demand**.



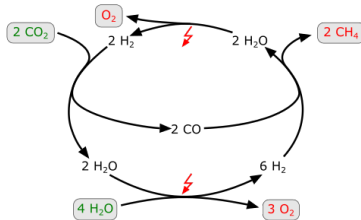
Efficiency of renewables and sector coupling



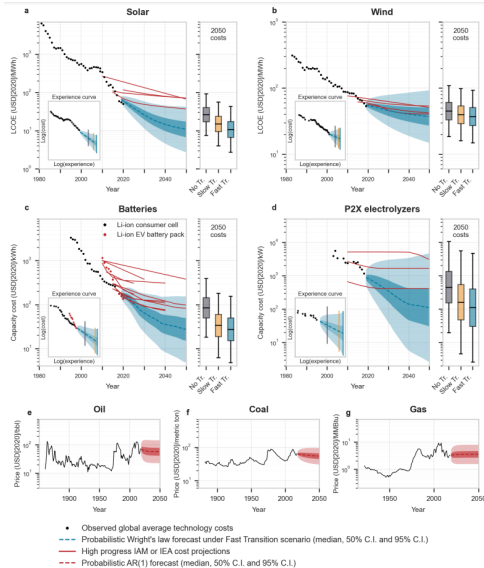


Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to **hydrogen** H_2 (and oxygen O_2). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH_4 (main component of natural gas) or liquid fuels C_nH_m . Used for **hard-to-defossilise sectors**:

- **dense fuels** for transport (planes, ships)
- **steel-making & chemicals industry**
- **high-temperature heat** or **heat for buildings**
- **backup energy** for cold low-wind winter periods, i.e. as storage



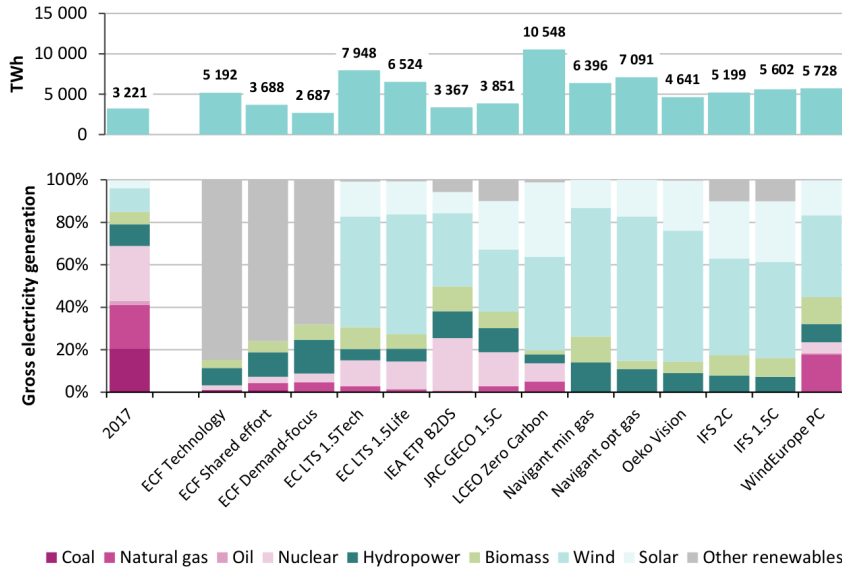
5 critical techs: wind, solar, batteries, heat pumps, electrolyzers



All critical techs for the energy transition share a small unit size, enabling fast production and installation, economies of scale in manufacturing and learning-by-doing.

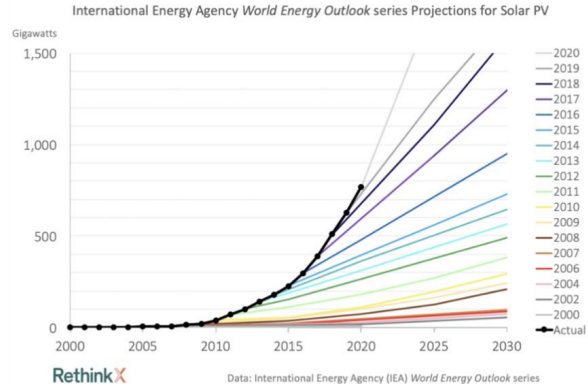
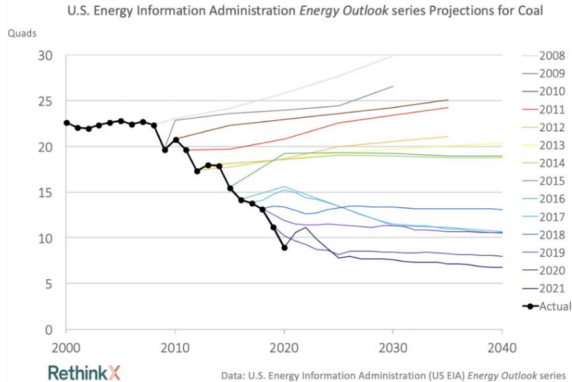
- **Low-cost electricity** from wind and solar.
- **Batteries** for mobility and balancing applications.
- **Electrolytic hydrogen** (splitting water) for everything else: long-duration storage, aviation, shipping, industry.
- **Heat pumps** (missing from graphic) for building comfort and some low-T industry.

2050 scenarios for EU: power demand doubles, mostly met by VRE



Not all predictions are reliable, especially about the future

We are working under **deep uncertainty**, with many potential **non-linear changes**.



Example Zero-Emission Systems

The following online toy model optimises a combination of wind, solar, batteries and hydrogen storage to meet a baseload demand, using weather data from any location in the world.

<https://model.energy/>

Look at the differences of wind and solar feed-in and optimal storage solutions for:

- **City: Berlin**
- **Country: Germany**
- **Continent: Europe**

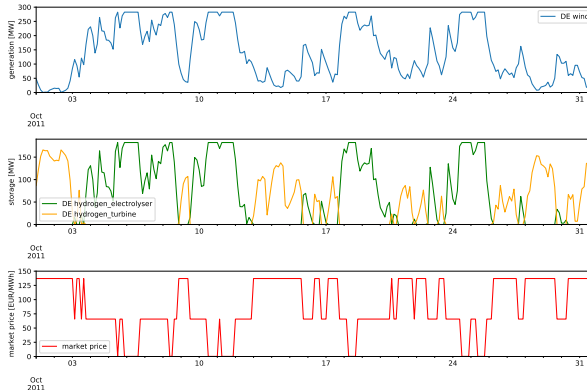
What do you notice?

Storage charges at low prices, discharges at high prices

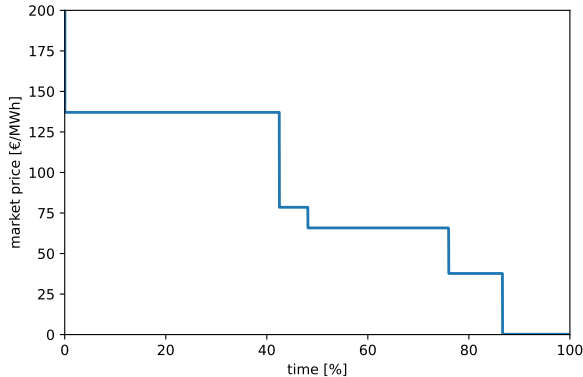
Simplified example from <https://model.energy> for Germany with only wind and hydrogen storage to meet a flat 100 MW demand.

Average charging price (with electrolyser): 43 €/MWh

Average discharging price (with turbine): 144 €/MWh



How are prices when there is only zero-marginal-cost wind/solar and storage but no fuels?

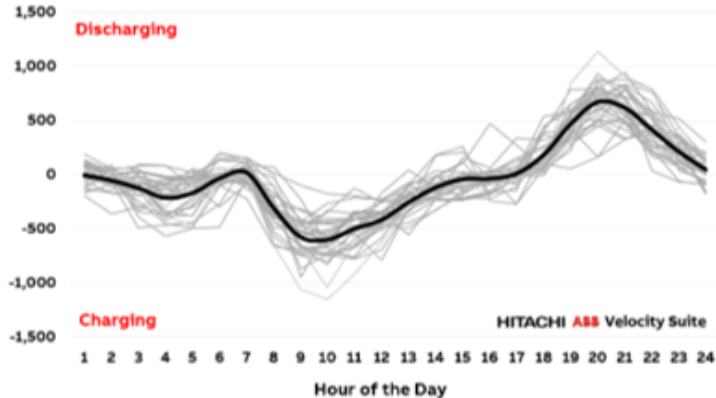


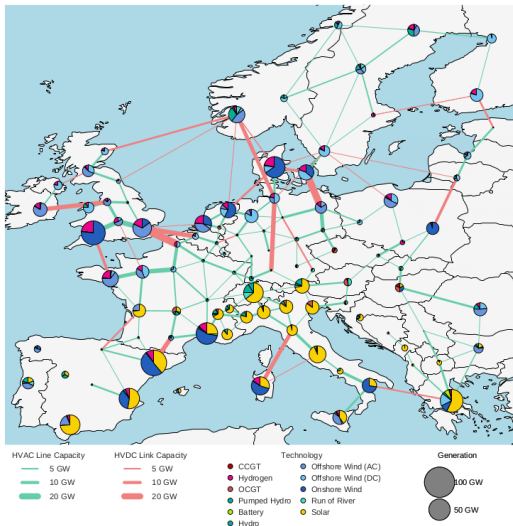
- When wind is scarce for $\sim 40\%$ of time, hydrogen turbine sets price high enough to cover their costs. Green hydrogen costs money, just like fossil fuel!
- Electrolyser is willing to bid more than zero for electricity (since it earns selling hydrogen to turbine), so demand sets non-zero price $\sim 45\%$ of time.
- Only when electrolyser is at capacity, do we curtail wind and price is zero $\sim 15\%$ of time.

Storage charges at low prices, discharges at high prices

We see batteries in California behaving exactly in this way today.

July 2021, MWh





For more detailed research-level modelling of future net-zero energy systems that include:

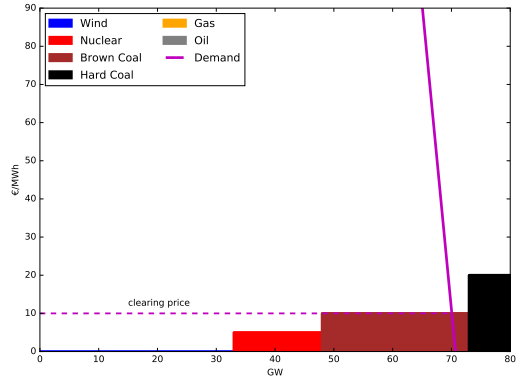
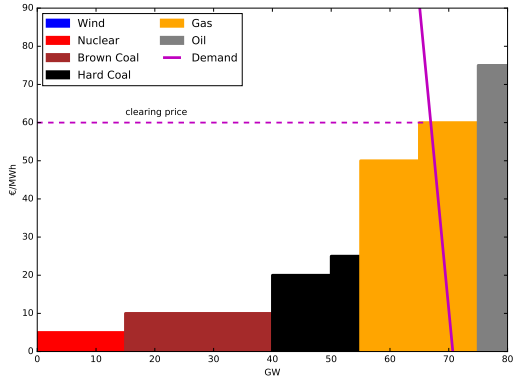
- All low-carbon generators
- Network modelling
- Other sectors (heating, transport, industry)
- Green hydrogen and materials
- Accounting for public acceptance

Come to the Energy Systems course in Summer Semester!

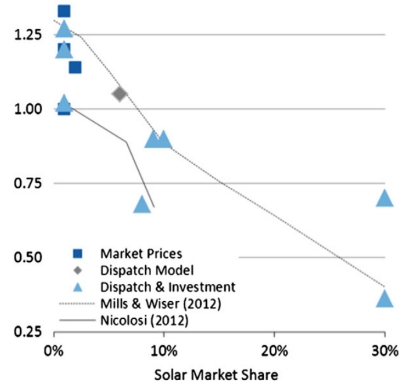
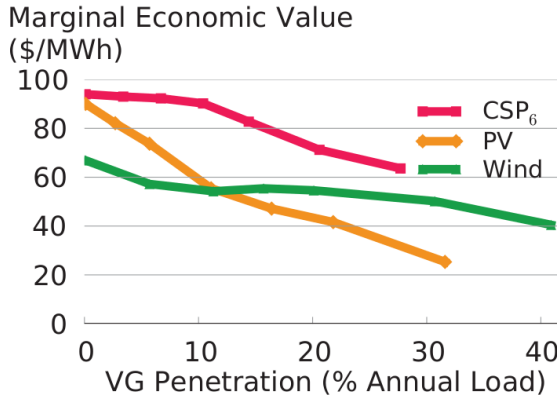
Market Integration of Renewables

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**'.



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



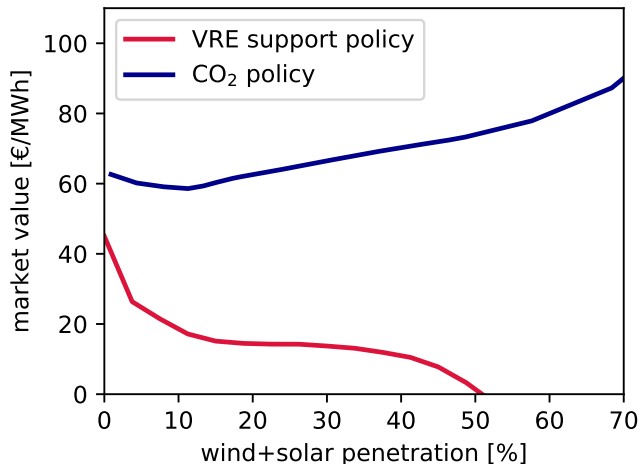
- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
- “Variability is the fundamental cause of market value decline.”
- “Declining market value implies wind and solar become uneconomical at high shares.”
- “Market integration of large shares of variable renewables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

- “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.”

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

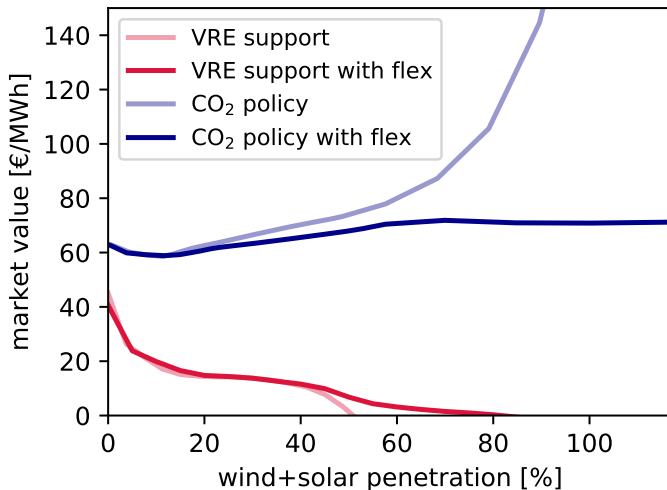
Implicit assumption in literature: VRE are forced in with subsidies or quotas, pushing MV down.

However, if VRE are drawn in with CO₂ pricing, MV does not decline.

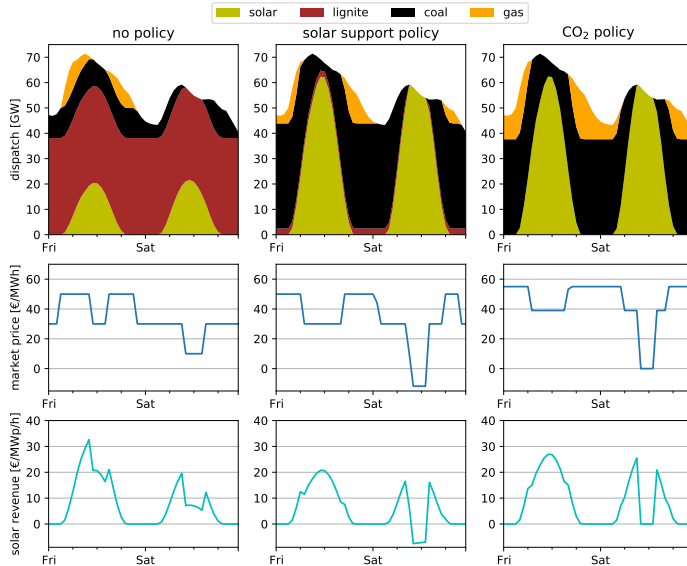


This holds even up to 100% wind and solar...

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



Example from primal perspective: solar support versus CO₂ pricing



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

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

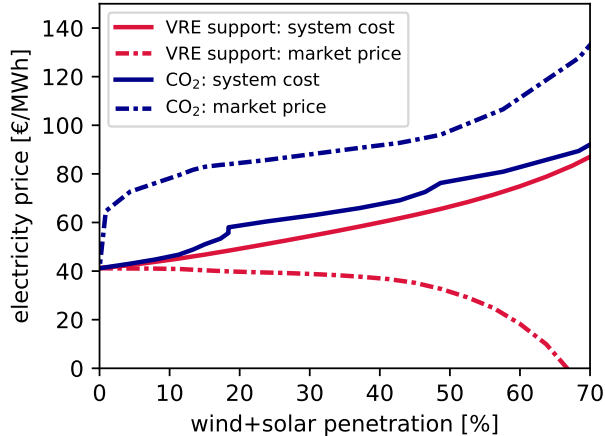
Dual perspective:

- Market value declines because share of generation is forced beyond equilibrium
- Policy is the fundamental cause
- Affects all generators which are forced beyond equilibrium

Perspectives and framing have consequences!

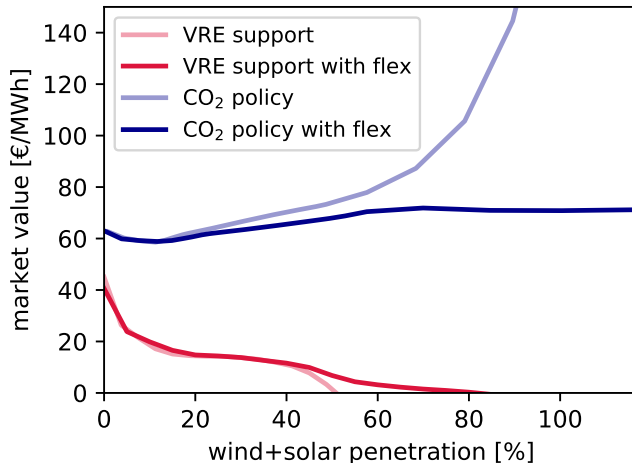
With VRE as the only low-C generators, system costs **barely differ** between policies.

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



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

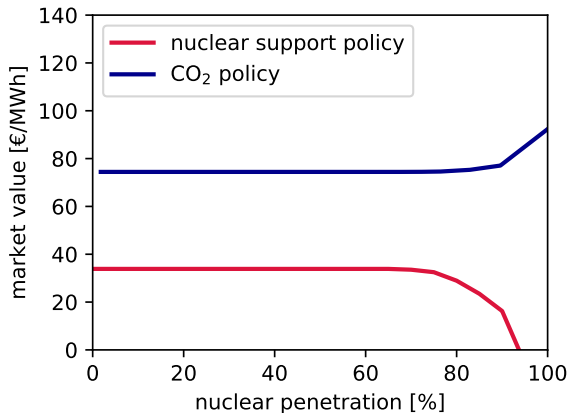
For CO₂ policies it **stabilises** LCOE = MV above penetrations of 70%.



Flexibility added here:

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

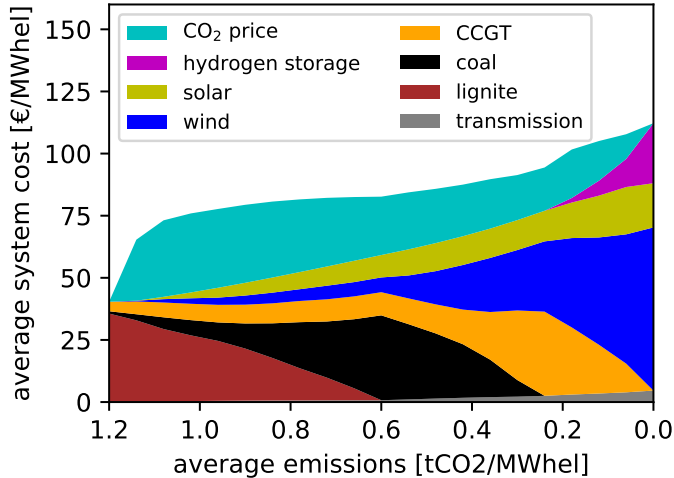
Nuclear revenue is also suppressed under a support policy, declining to zero at high penetrations because of the variable demand. A CO₂ price avoids this behaviour.



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

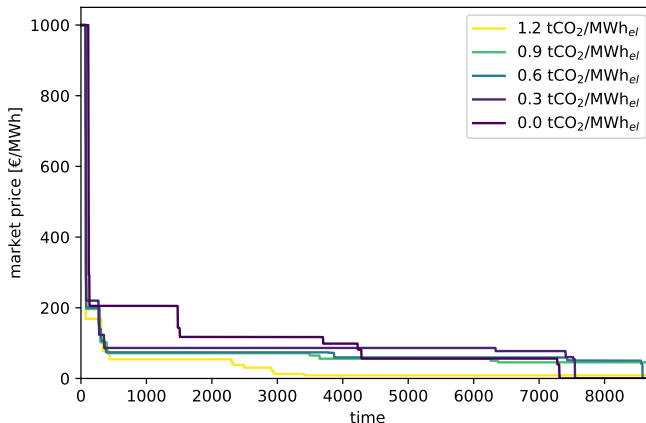
⇒ **Policy is responsible for MV decline**, variability only affects the speed.

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



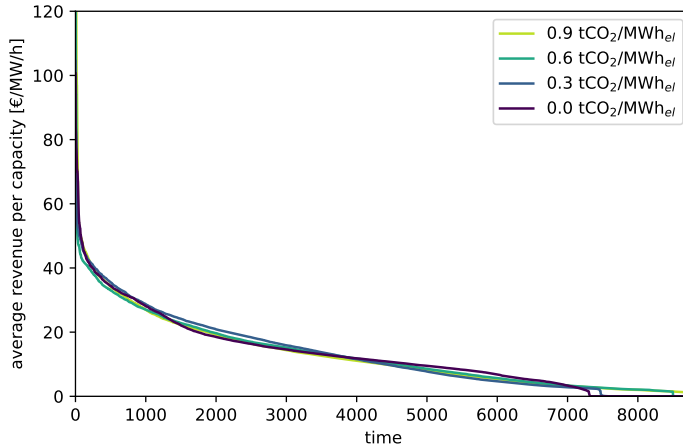
CO₂ price raises prices when fossil generators on margin, but also storage bids **high opportunity costs** when discharging, while charging bids reduce hours when prices are zero.

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



The distribution of hours when VRE earns its money barely changes as CO₂ emission reduce.

⇒ VRE does not become dependent on only a small number of hours to make money.

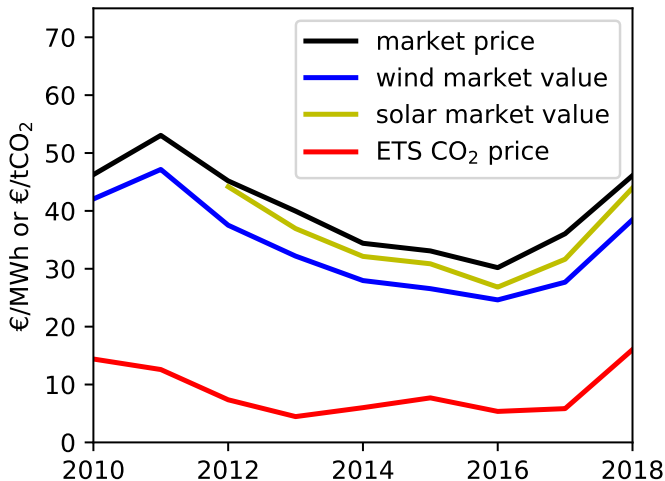


- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
 - **No**, if drawn in with a CO₂ price, market value does not decline.
- “Variability is the fundamental cause of market value decline.”
 - **No**, policy is the fundamental cause (no policy, no decline), but 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.

- 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

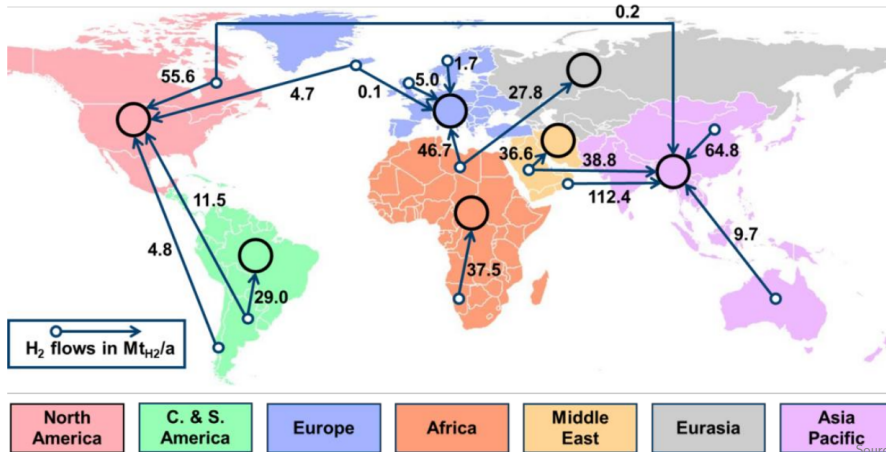
Further reading: Brown & Reichenberg, “Decreasing market value of variable renewables can be avoided by policy action,” Energy Economics (2021), [doi:10.1016/j.eneco.2021.105354](https://doi.org/10.1016/j.eneco.2021.105354).

Before 2016 market value declines with rising subsidies; after 2016 it rises as CO₂ prices rise.



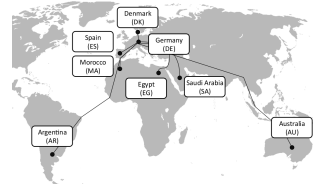
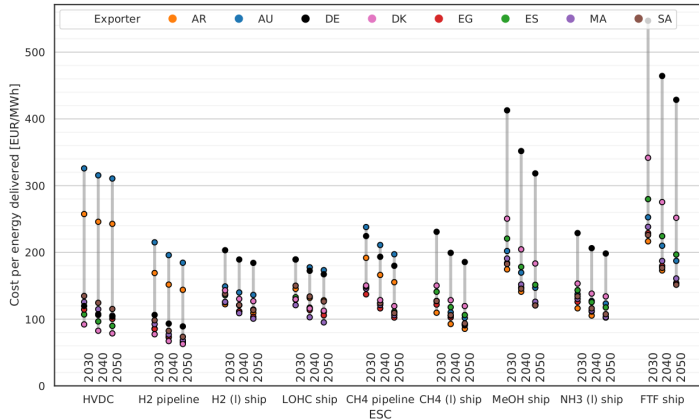
Markets for Green Fuels

Today fossil fuels are traded across the globe. Electrolytic-hydrogen-based synthetic fuels (e.g. hydrogen, ammonia, methane, liquid hydrocarbons and methanol) could also be piped/shipped worldwide. Possible future scenario for hydrogen trade from Helmholtz colleagues at FZJ IEK-3:



Synthetic fuels from outside Europe?

Green hydrogen with pipeline transport costs around ~ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.



The German H2Global scheme provides support for the production of renewable hydrogen in non-EU countries, to be imported and sold in the EU.

It makes available €900 million over 10 years to cover the difference between production costs and what consumers are willing to pay.

This difference is determined by a double auction: producers bids for **hydrogen purchase agreements (HPA)** that run for 10 years, providing investment security, while consumers bid for hydrogen service agreements (HSA) of duration one year.

H2Global was approved by the European Commission to comply with EU state aid rules in December 2021. It was topped up from €900 million to €4 billion in 2022. See [H2Global website](#).

The EU will also start a €3 billion [European Hydrogen Bank](#) in 2023.

Could end up in a situation with following characteristics:

- Most electricity is **sourced locally** from variable wind and solar
- Backup is provided either by **electricity storage** or **imported hydrogen-based fuels**
- Many demand sectors are **directly electrified** (e.g. heat pumps in buildings, electric vehicles in transport) or with green-hydrogen-based fuels (e.g. industry)
- Hydrogen-based liquid fuels (ammonia, methanol, diesel/kerosene) and materials (direct-reduced iron) are **traded globally**
- Since wind and solar can be found everywhere, less market concentration than fossil fuels
⇒ **geopolitical reordering** (different countries have relevant resources, market power of producers is weakened, shift to more capex-intensive energy sector)