

# Energy Economics, Winter Semester 2025-6

## Lecture 13: The Future

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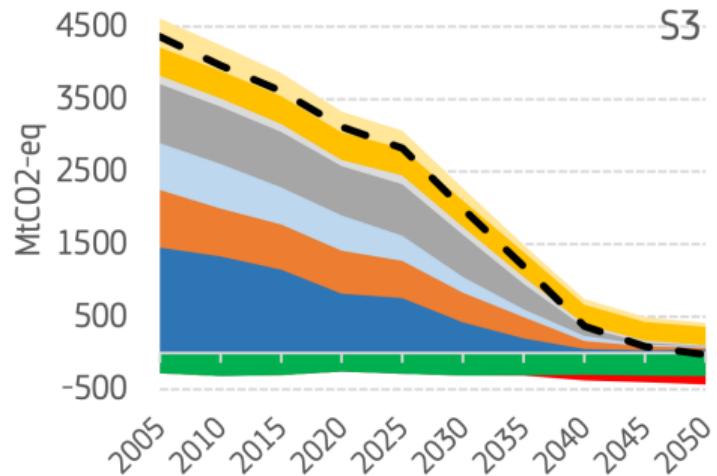
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## Possible Pathways

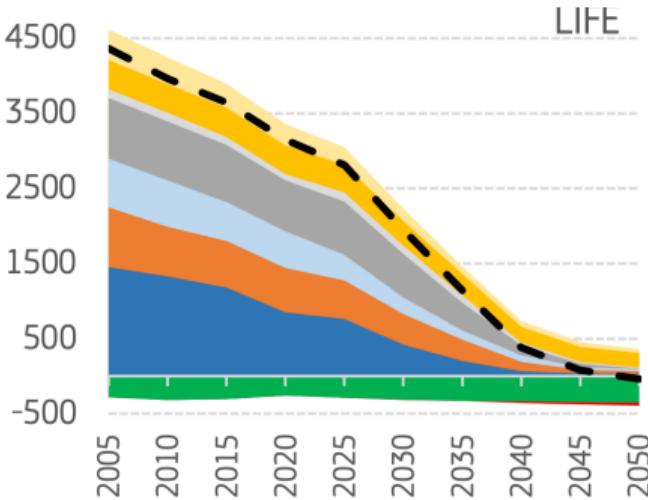
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# The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

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**.

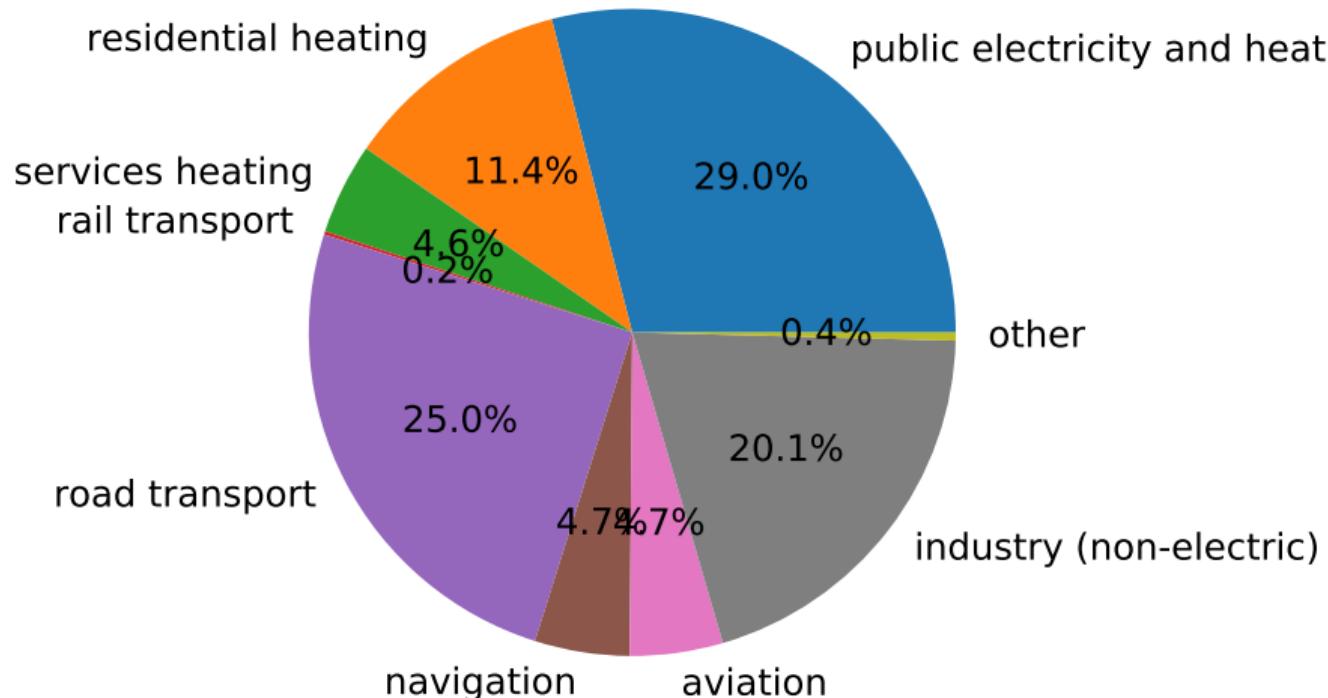


Ind. Removals  
Non-CO<sub>2</sub> in non Land-related sectors  
Int. Transport  
Buildings  
En. Supply



LULUCF  
Agriculture  
Domestic Transport  
Industry  
Net GHG emissions

EU28 CO<sub>2</sub> emissions in 2016 (total 3.5 Gt CO<sub>2</sub>, 9.7% of global):

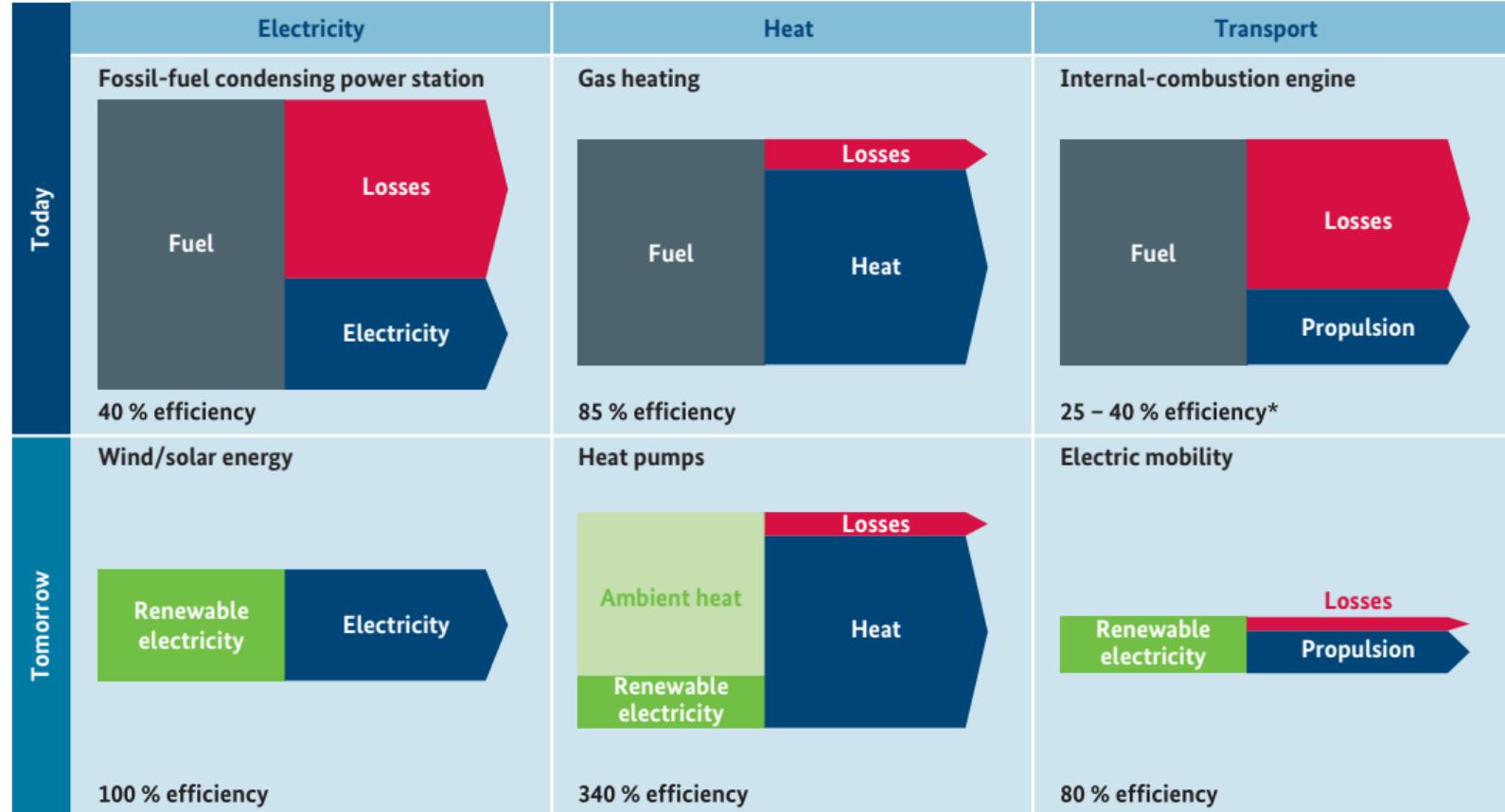


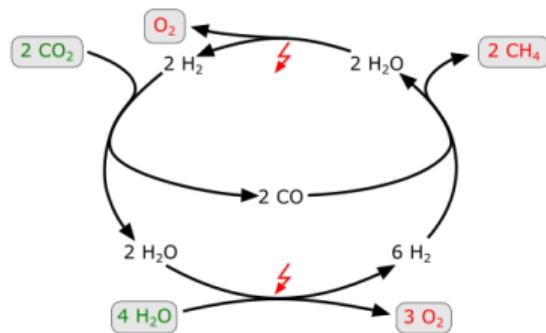
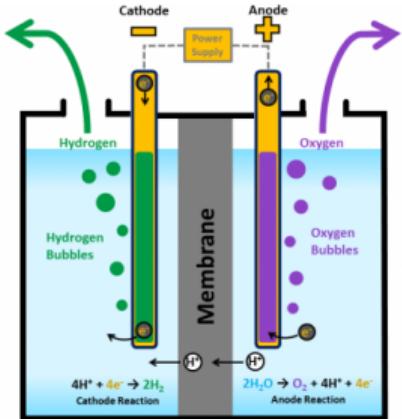
**Electrification is essential** to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

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



# Efficiency of renewables and sector coupling

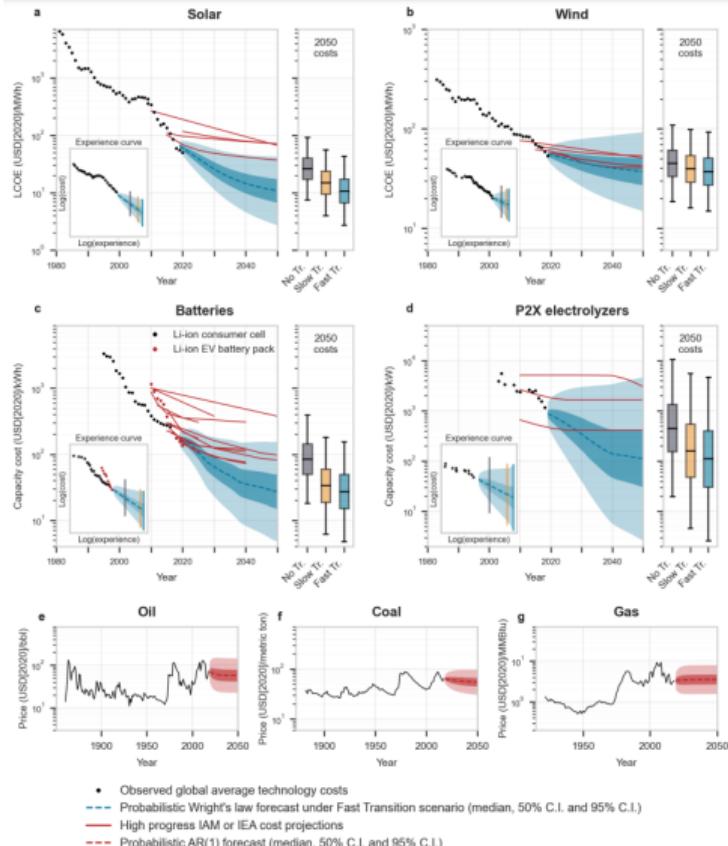




Power-to-Gas/Liquid (P2G/L) describes concepts to use electricity to electrolyse water to **hydrogen** H<sub>2</sub> (and oxygen O<sub>2</sub>). We can combine hydrogen with carbon oxides to get **hydrocarbons** such as methane CH<sub>4</sub> (main component of natural gas) or liquid fuels C<sub>n</sub>H<sub>m</sub>. 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

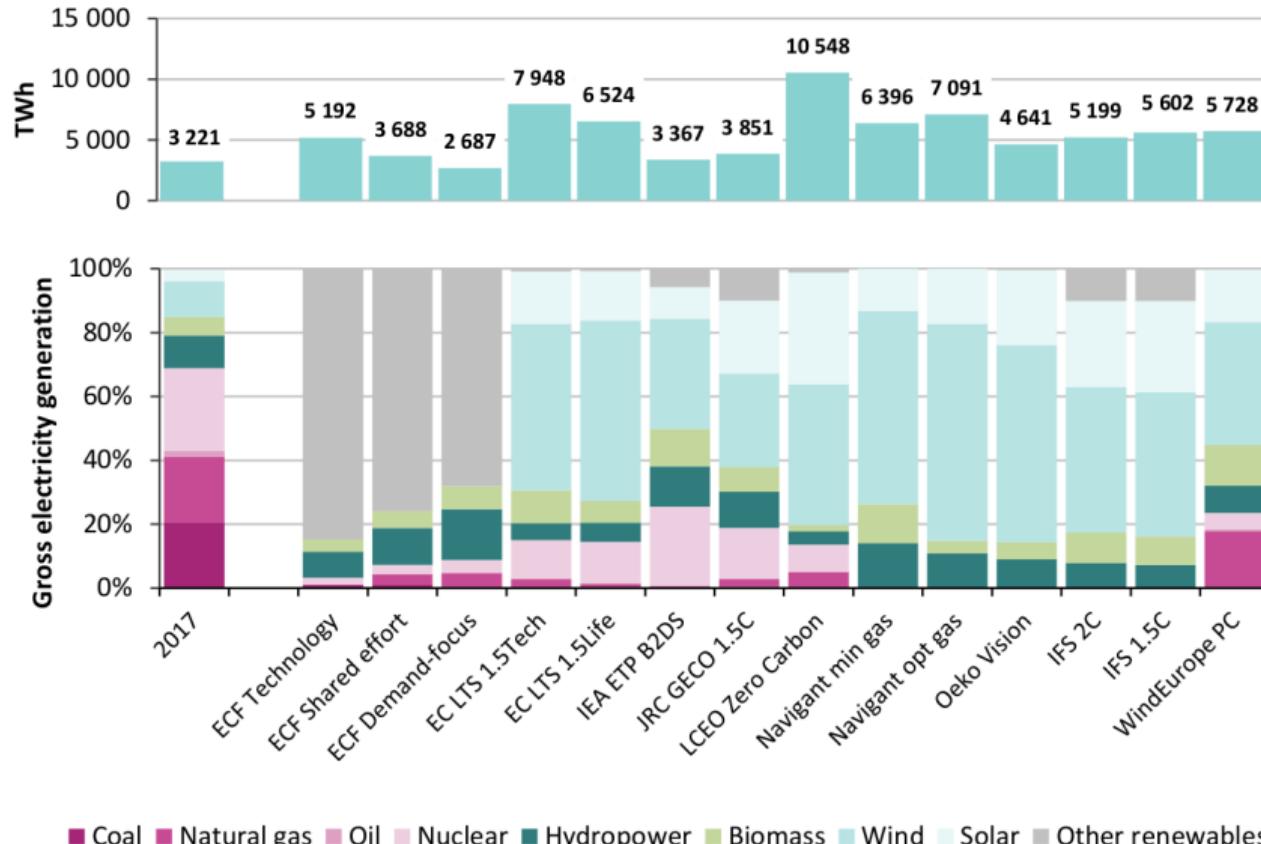
# 5 critical techs: wind, solar, batteries, heat pumps, electrolyzers



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.

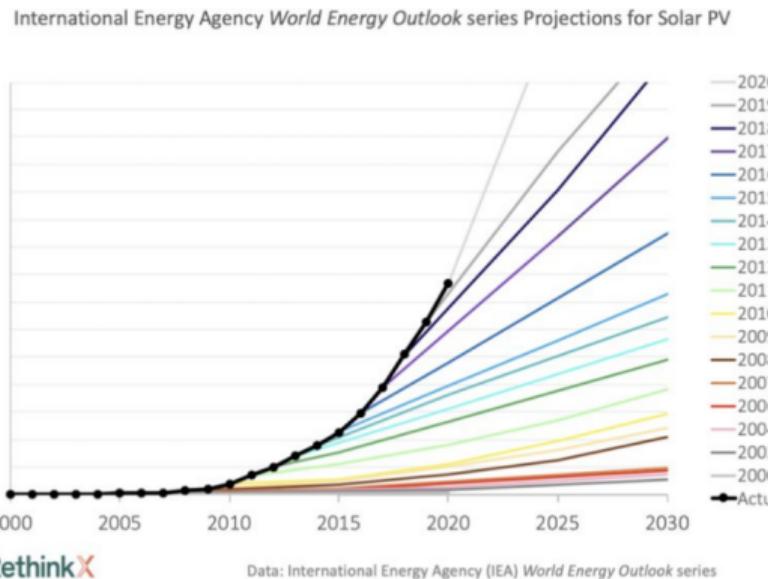
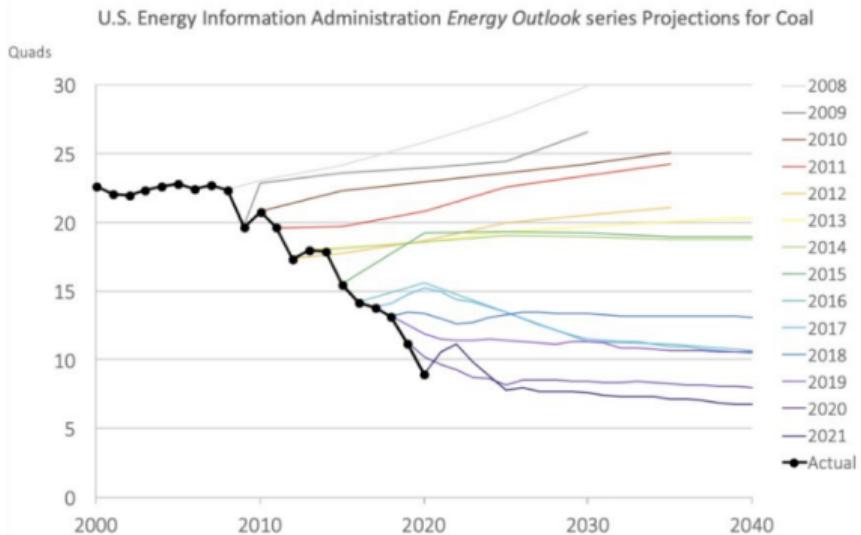
- **Low-cost electricity** from wind and solar.
- **Batteries** for mobility and balancing applications.
- **Electrolytic hydrogen** (splitting water) for everything else: long-duration storage, aviation, shipping, industry.
- **Heat pumps** (missing from graphic) for building comfort and some low-T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

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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**

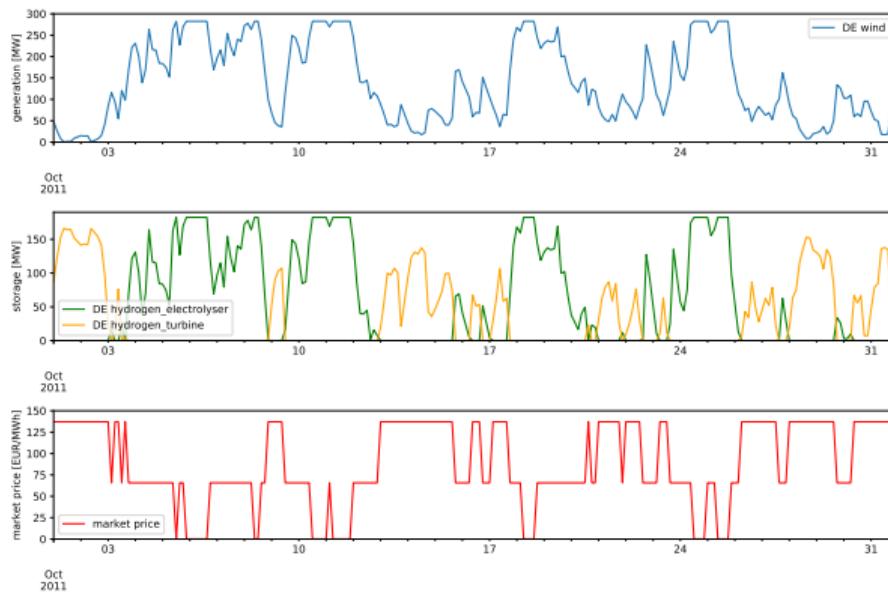
What do you notice?

# 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.

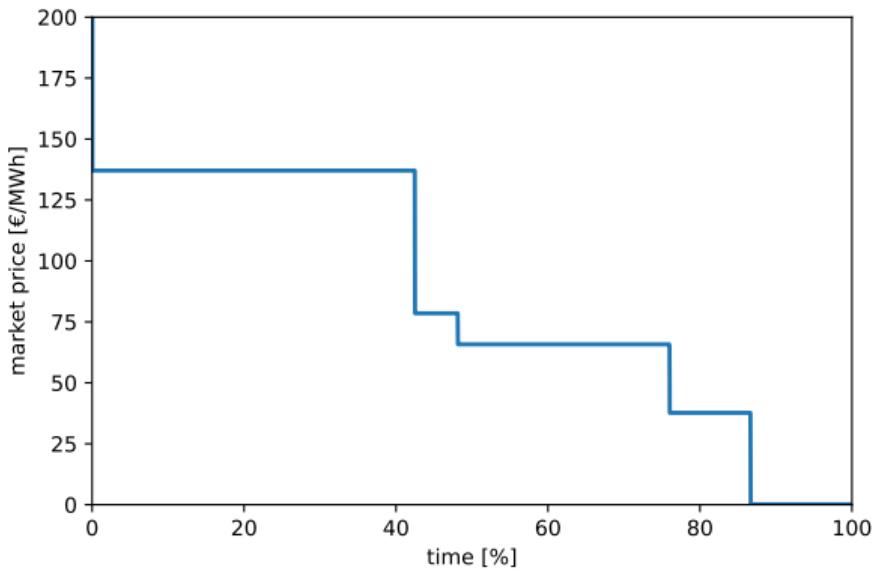
Average charging price (with electrolyser): 43 €/MWh

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



# Storage charges at low prices, discharges at high prices

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

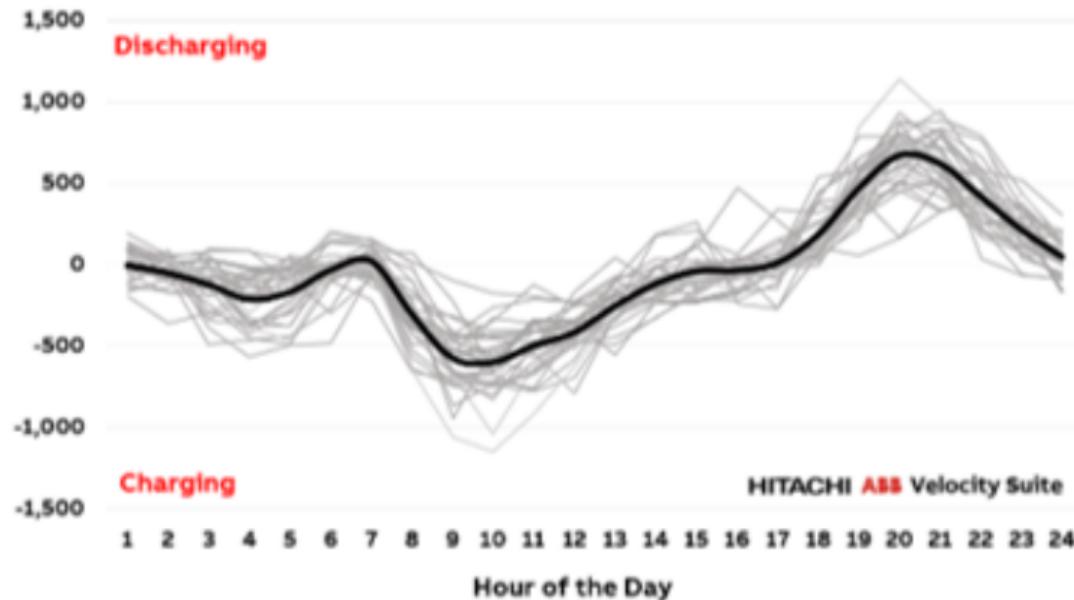


- When wind is scarce for ~40% of time, hydrogen turbine sets price high enough to cover their costs. Green hydrogen costs money, just like fossil fuel!
- Electrolyser is willing to bid more than zero for electricity (since it earns selling hydrogen to turbine), so demand sets non-zero price ~45% of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

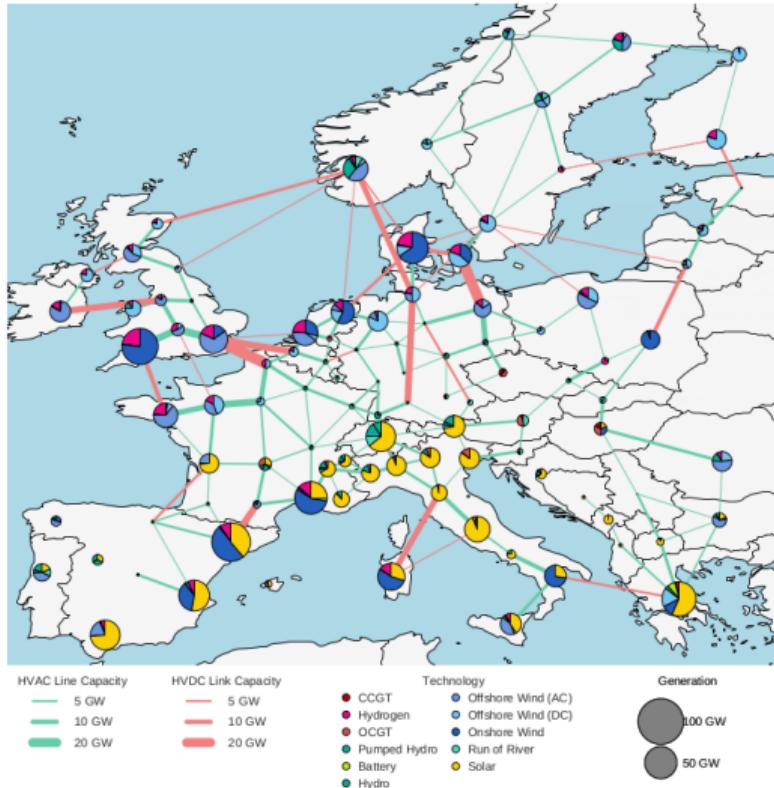
# Storage charges at low prices, discharges at high prices

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

**July 2021, MWh**



# More Detailed Modelling



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

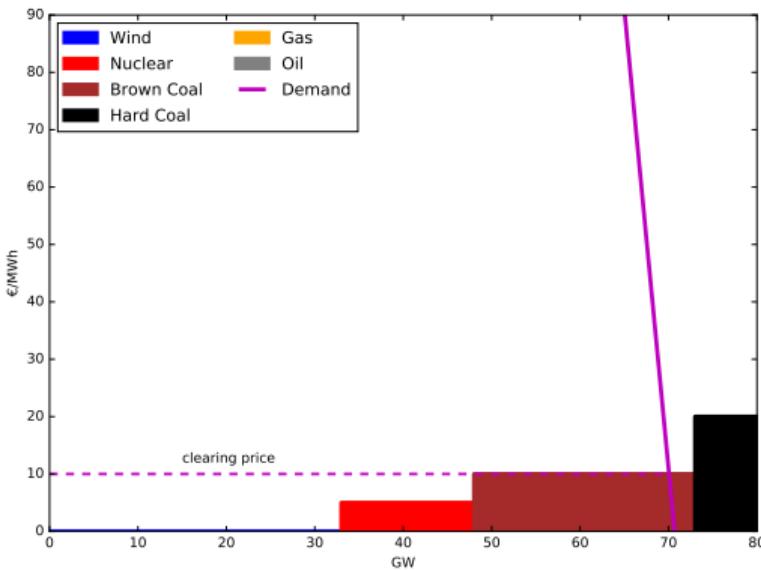
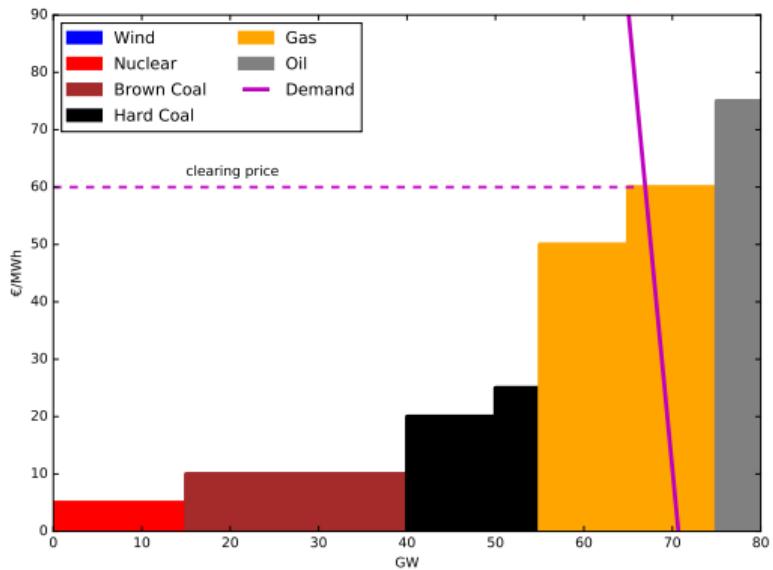
Come to the Energy Systems course in Summer Semester!

## **Market Integration of Renewables**

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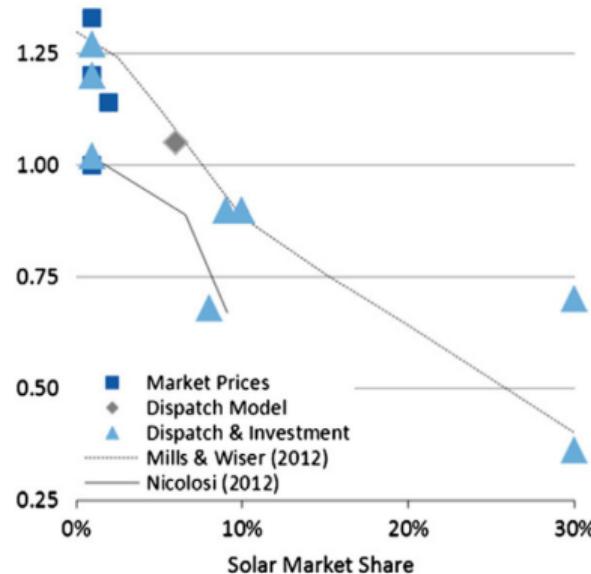
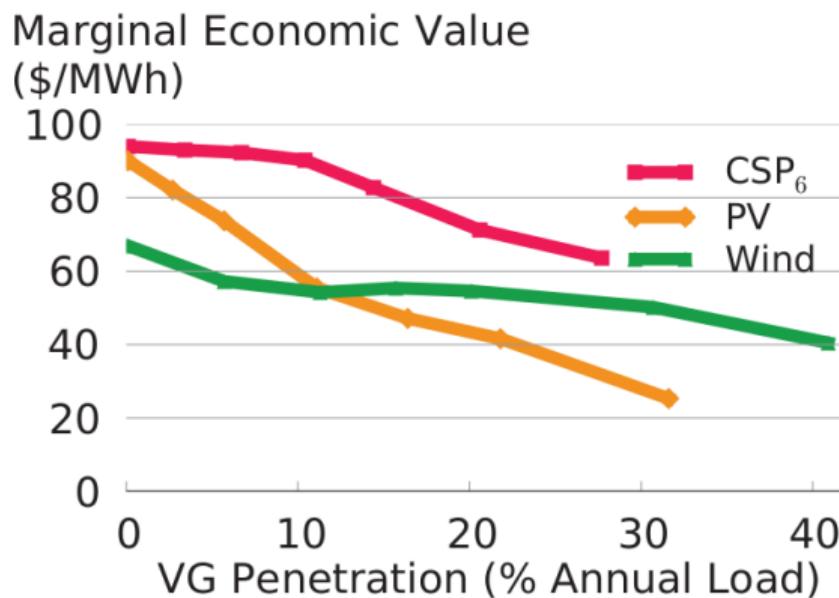
# Traditional 'primal' view of market value of wind and solar

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**.



- “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.”

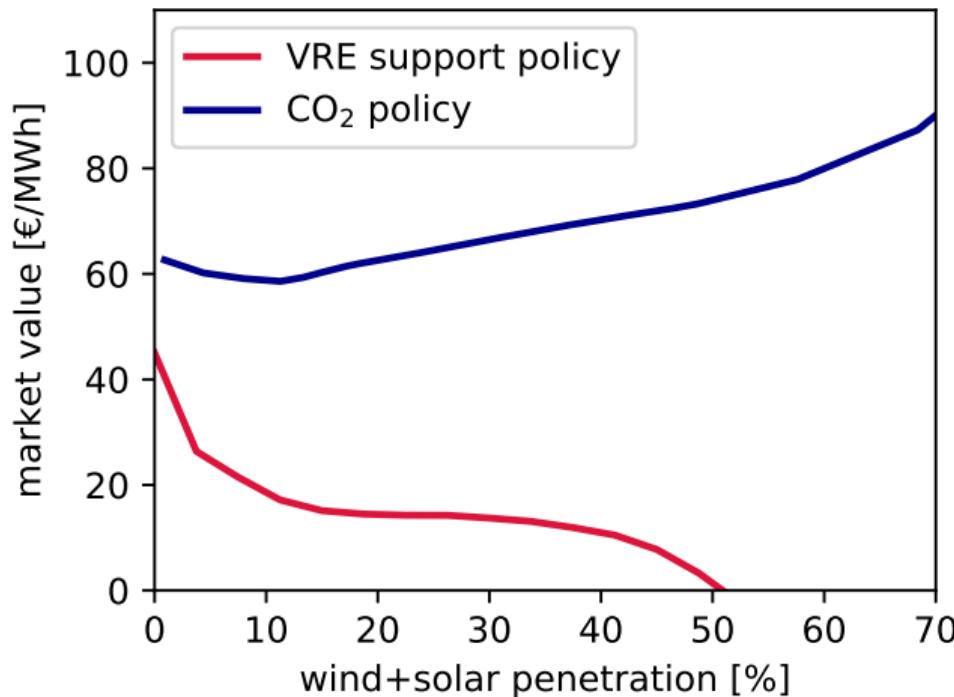
- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
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We show that from a **dual perspective**, each of these statements is **wrong**.

# Market value decline depends on market structure

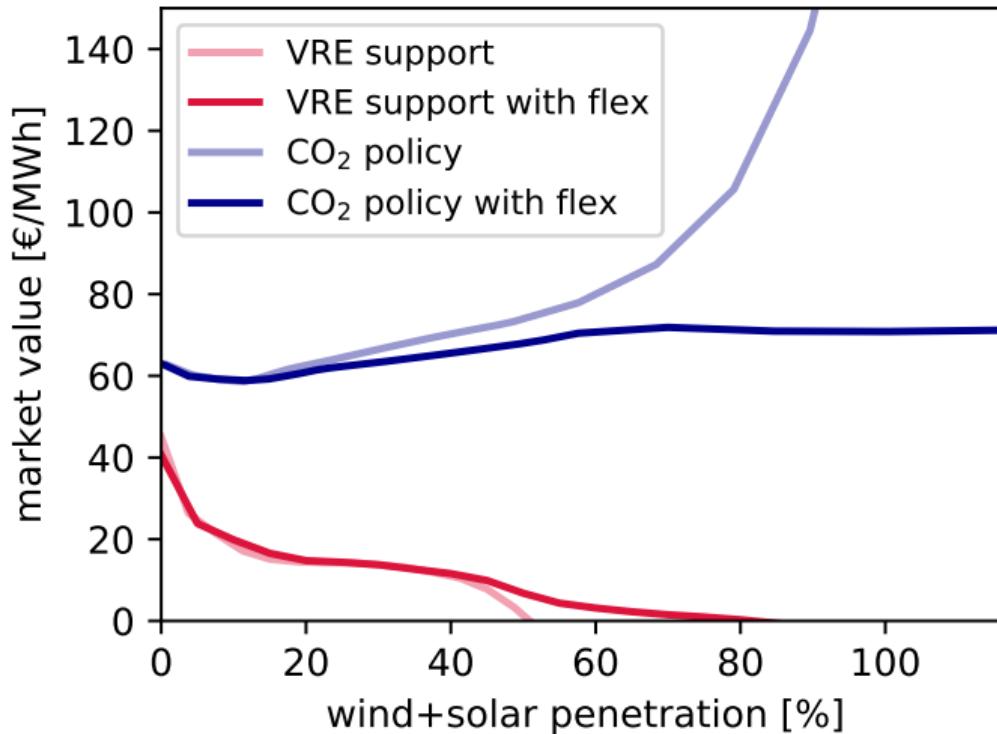
Implicit assumption in literature: VRE are forced in with subsidies or quotas, pushing MV down.

However, if VRE are drawn in with CO<sub>2</sub> pricing, MV does not decline.

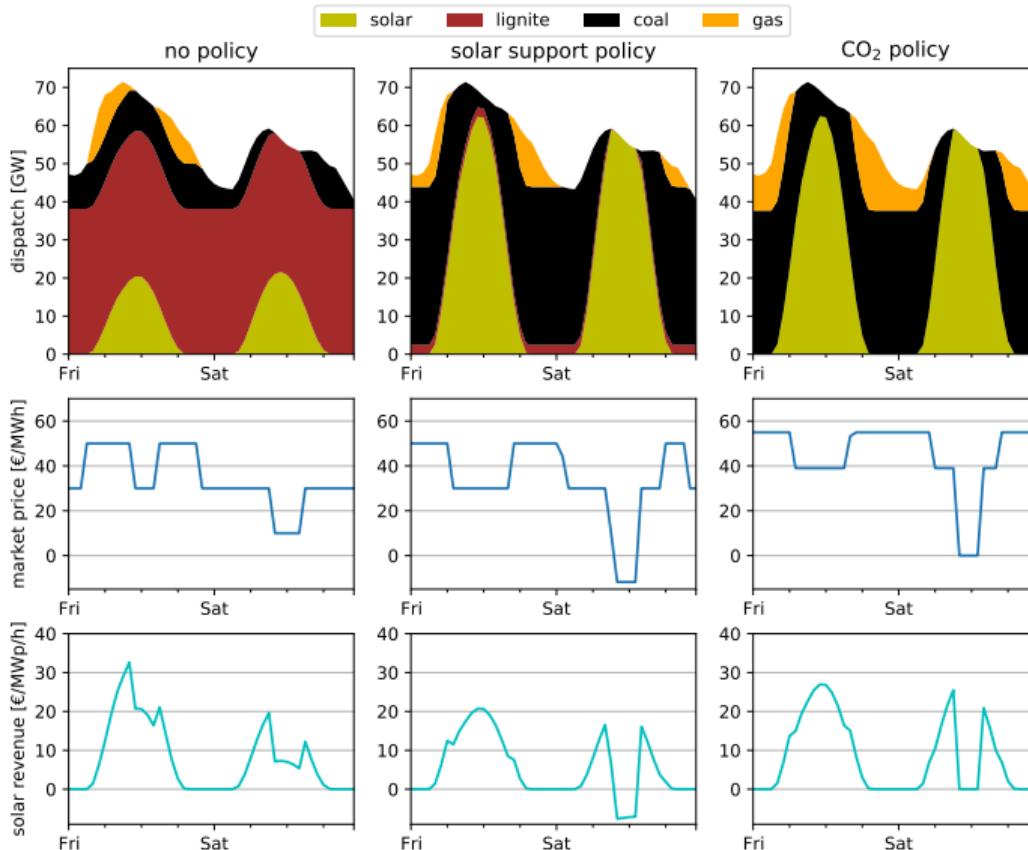


# This holds even up to 100% wind and solar...

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



# Example from primal perspective: solar support versus CO<sub>2</sub> 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
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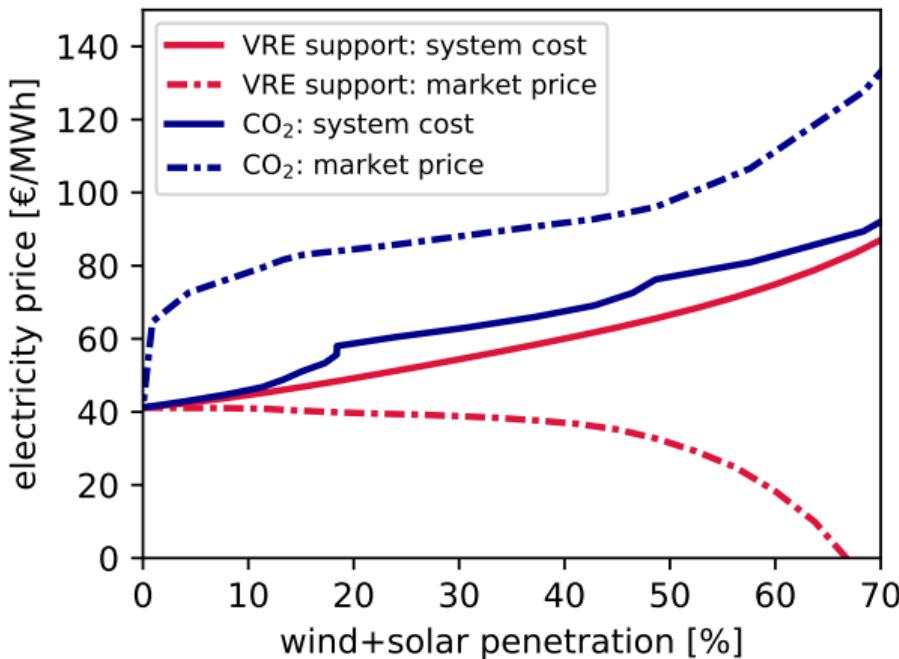
## Dual perspective:

- 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.

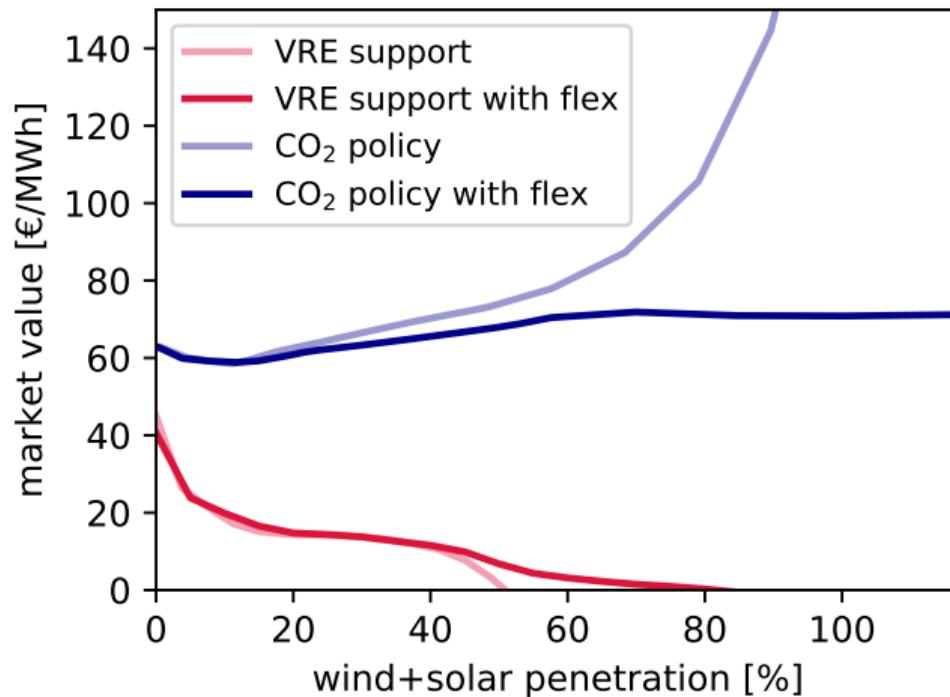
⇒ MV collapse under support policy does not necessarily indicate system is pathological.



# Role of flexibility

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

For CO<sub>2</sub> policies it **stabilises** LCOE = MV above penetrations of 70%.

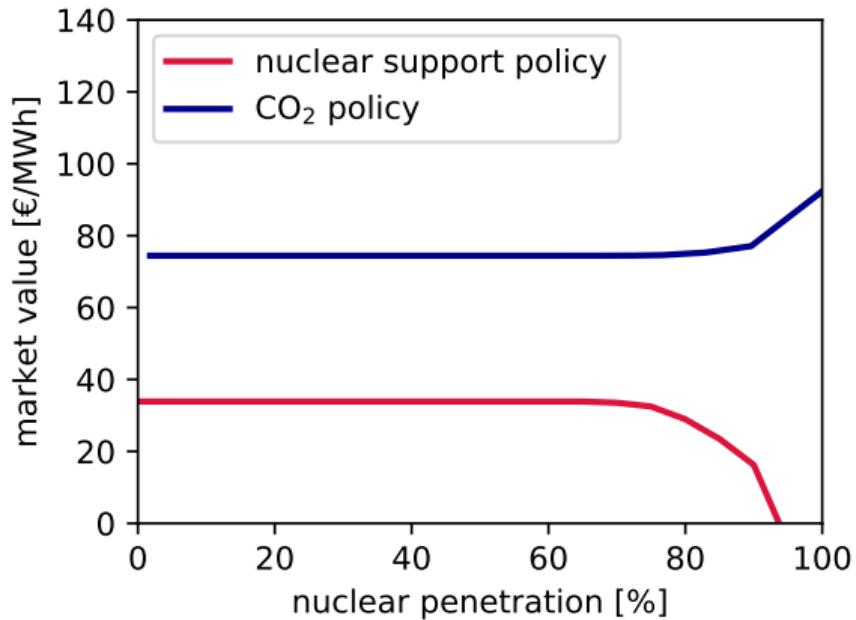


Flexibility added here:

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

## 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<sub>2</sub> price avoids this behaviour.

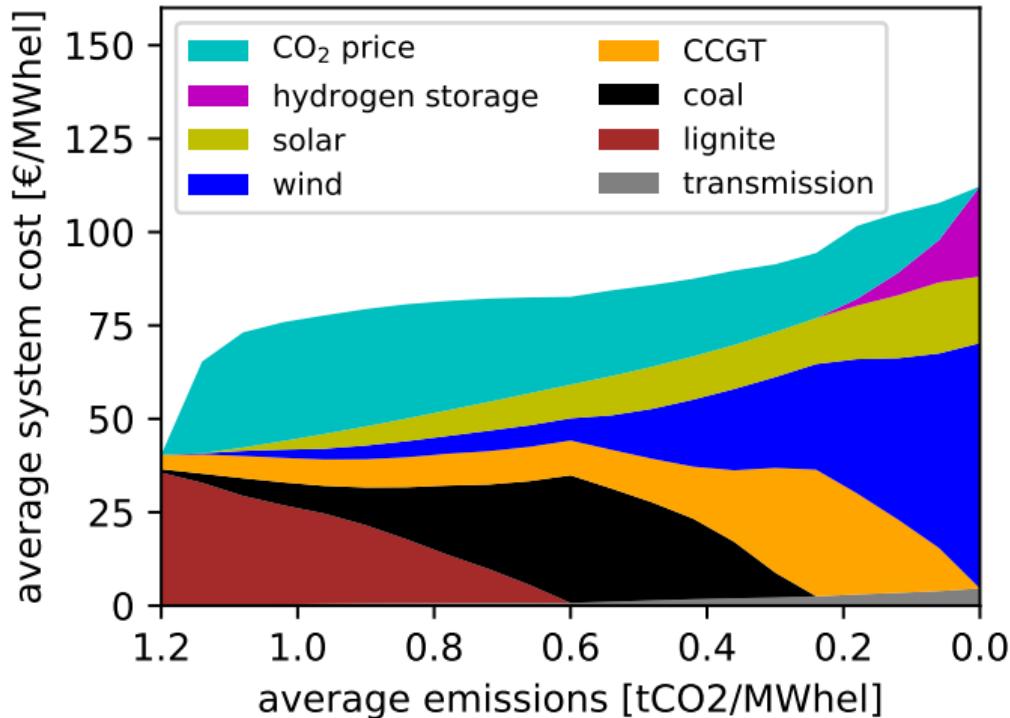


⇒ Nothing specific to VRE about MV suppression.

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

# System costs for CO<sub>2</sub> policy

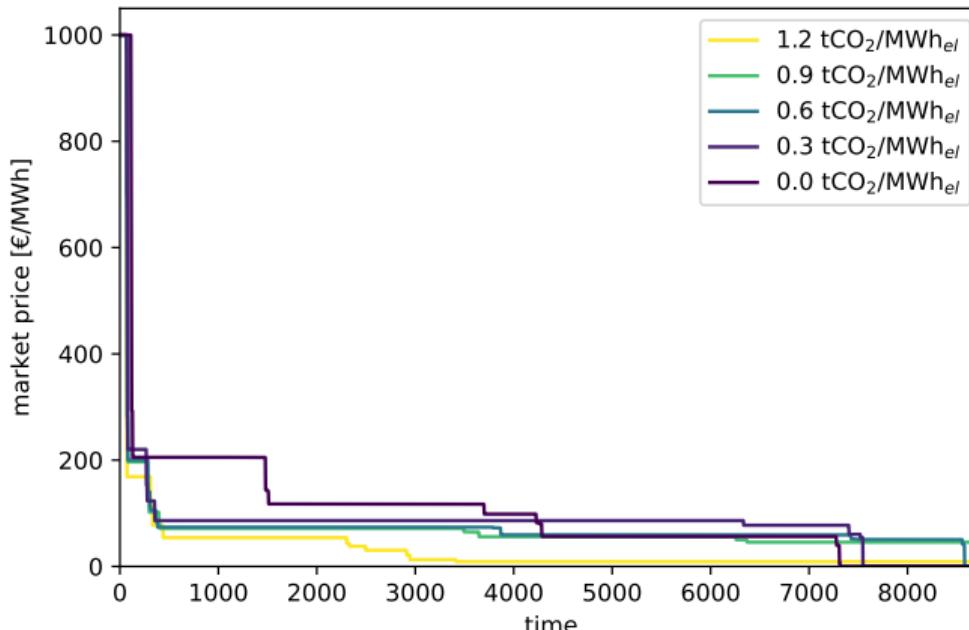
In breakdown of system costs, hydrogen storage balances the system at high penetrations.



# Price duration curves under a CO<sub>2</sub> policy

CO<sub>2</sub> 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.

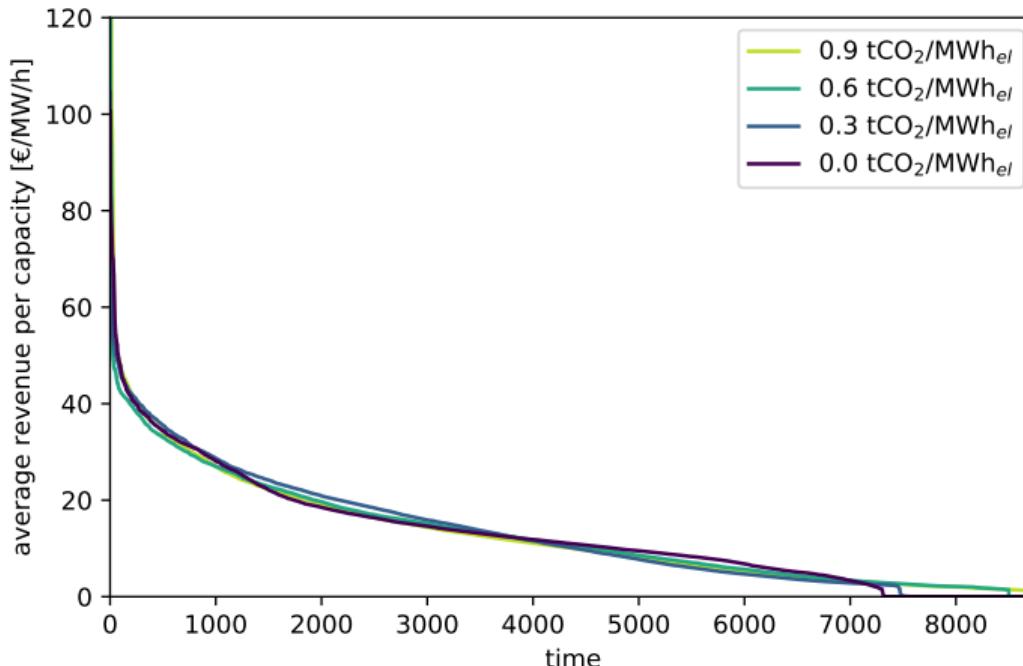
⇒ Market does not degenerate into bifurcation of prices between zero and very high.



## Average revenue per capacity per hour

The distribution of hours when VRE earns its money barely changes as  $\text{CO}_2$  emission reduce.

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

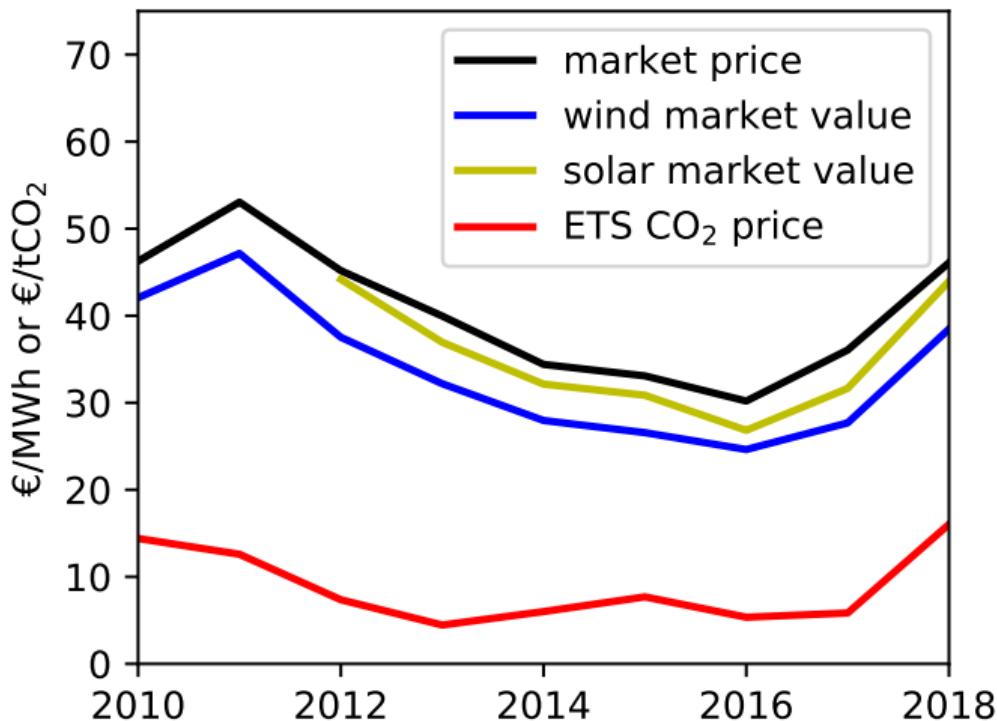


- “Market value of wind and solar always declines with penetration - VRE eat own revenue.”
  - **No**, if drawn in with a CO<sub>2</sub> price, market value does not decline.
- “Variability is the fundamental cause of market value decline.”
  - **No**, policy is the fundamental cause (no policy, no decline), 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 CO<sub>2</sub> 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<sub>2</sub> reduction)
- Can **combine** CO<sub>2</sub> 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 CO<sub>2</sub> prices rise.

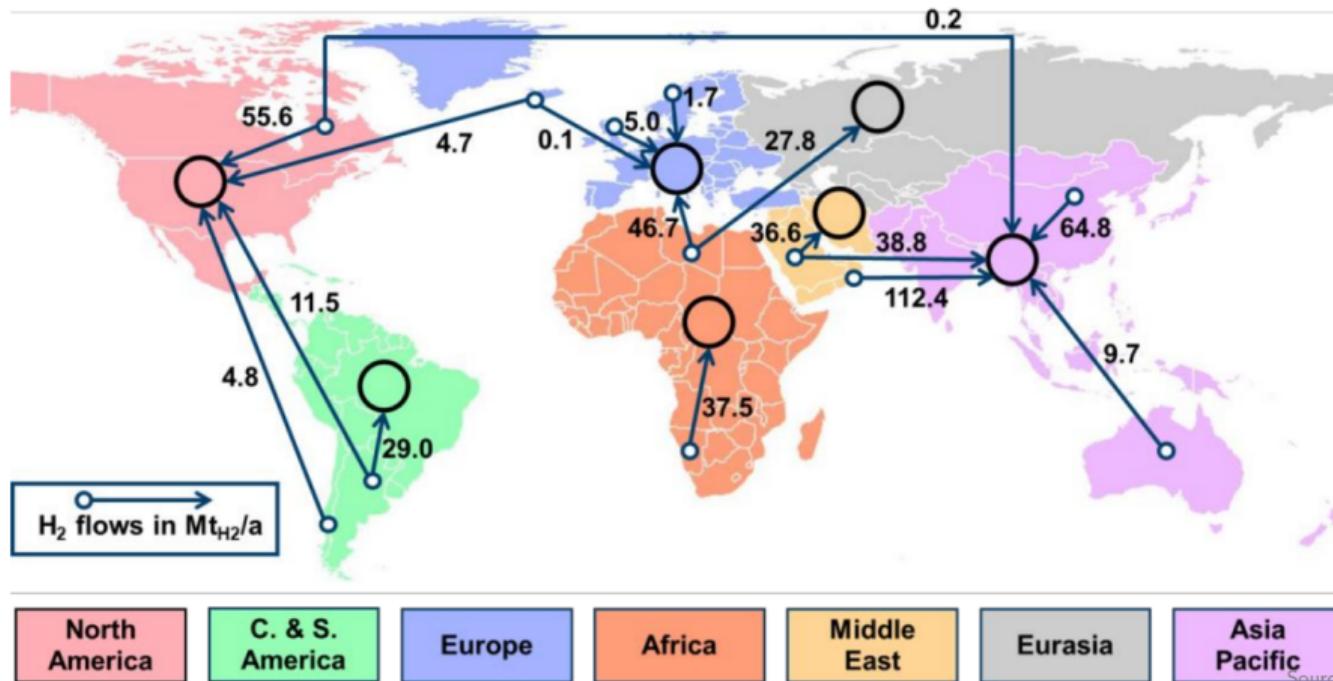


## Markets for Green Fuels

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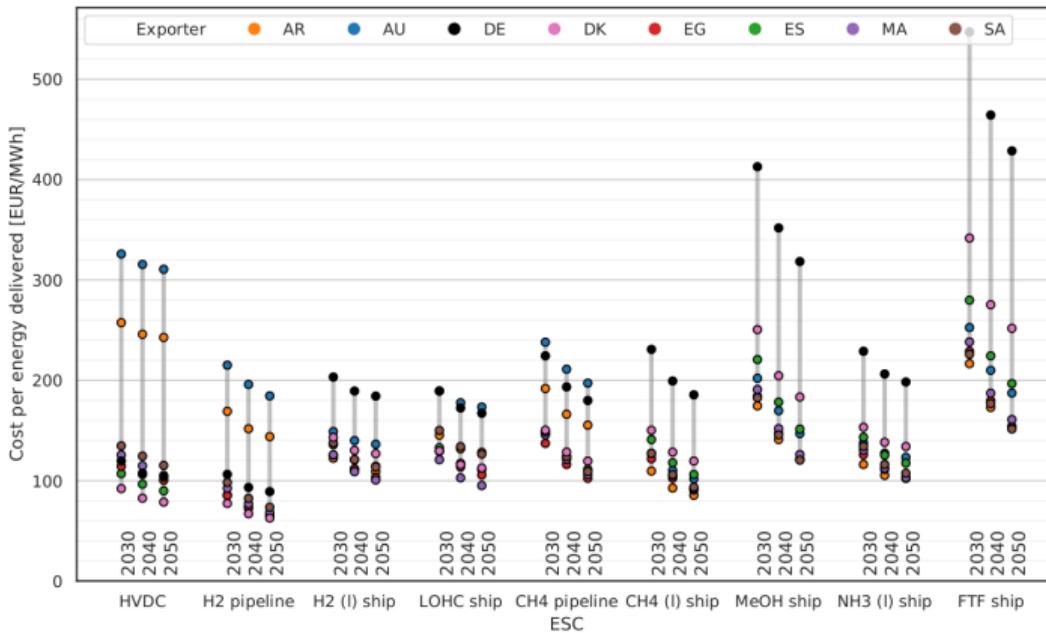
# Worldwide trade in synthetic fuels

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  $\sim 80$  €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH<sub>3</sub> 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)