NTNU
Norwegian University of Science and Technology

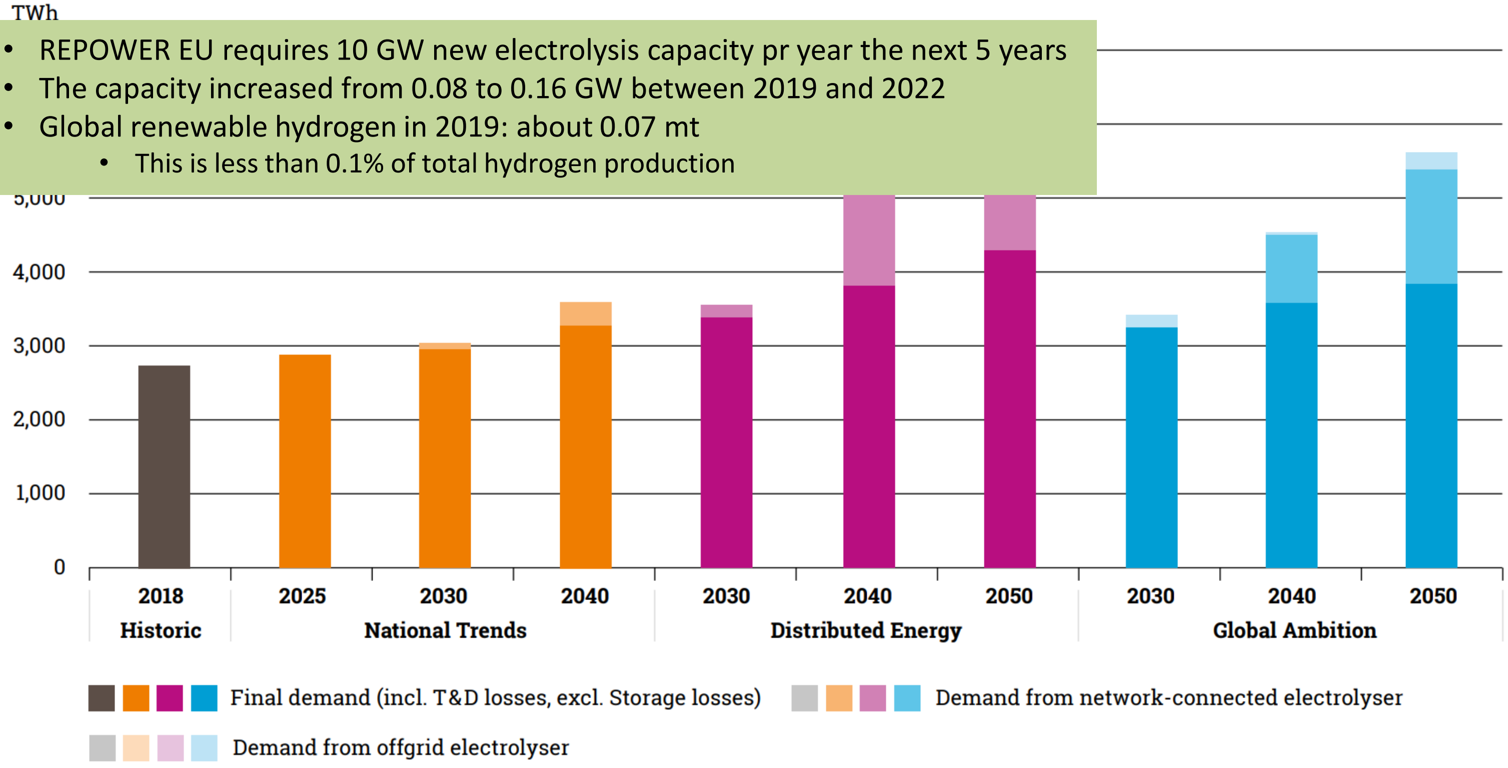
Optimal mix and dispatch of resources in low-carbon energy systems

Magnus Korpås
Professor, Electricity Markets and Energy System Planning Group
Dept. of Electric Energy, NTNU
Leader of WP Markets, IEA TCP Wind Task 25

IEA Wind #TEM113, Dublin
8-9th April, 2024

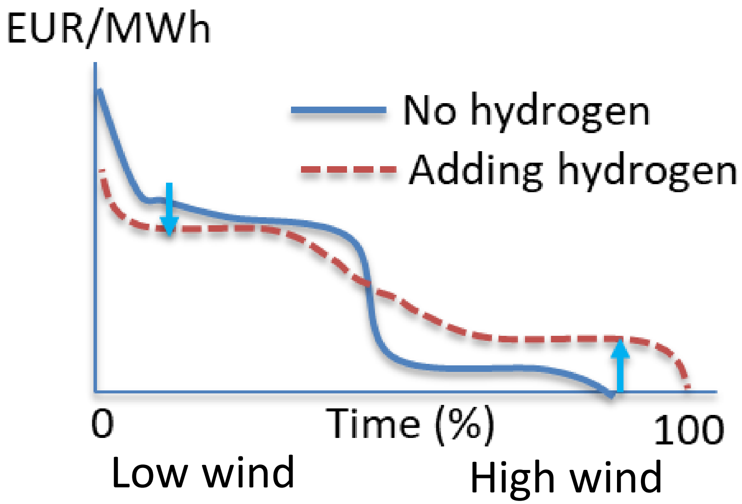
EU Electricity demand including hydrogen

- REPOWER EU requires 10 GW new electrolysis capacity pr year the next 5 years
- The capacity increased from 0.08 to 0.16 GW between 2019 and 2022
- Global renewable hydrogen in 2019: about 0.07 mt
    - This is less than 0.1% of total hydrogen production



Hydrogen flexibility can increase value of wind and solar

- Hydrogen flexibility will lift the lowest prices
  - Produce hydrogen when there is surplus wind&solar
- Makes wind and solar more profitable → Attractive to invest more → Lower prices

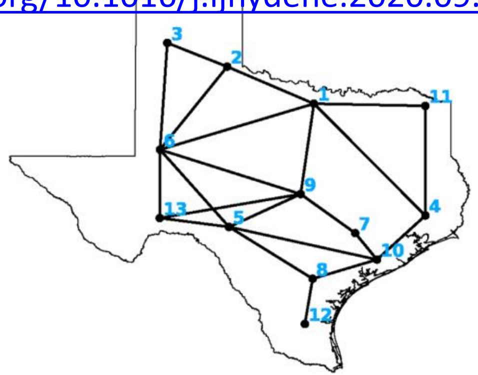


But this requires enormous amounts of cheap and easily accessible hydrogen underground storage

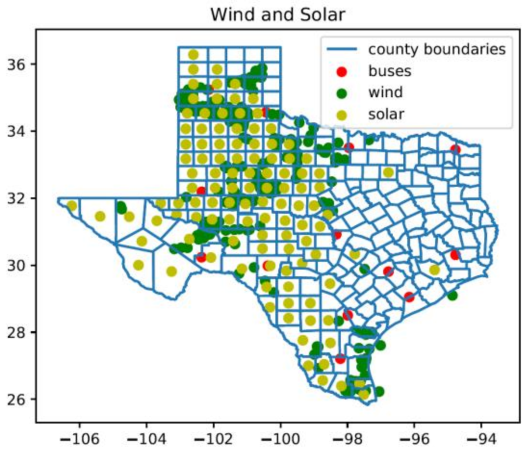
Results from NTNU/MIT cooperation 2020: https://doi.org/10.1016/j.ijhydene.2020.09.127

Case study: Texas

- We model the Texas electric power system towards year 2050
- The electric power system is **dominated by natural gas**
- **Significant wind power** is developed the latest years
- Texas has high potential for development of renewables
  - Located in the north-west or south
  - Most energy demand is in the east
- **Already high H2 demand in industry**
- H2 demand scenarios for transportation:
  - Moderate / High / Extremely high (!)
- Electricity demand 492 TWh (42% increase from 2018)
- Tech costs mainly from NREL 2050 scenarios



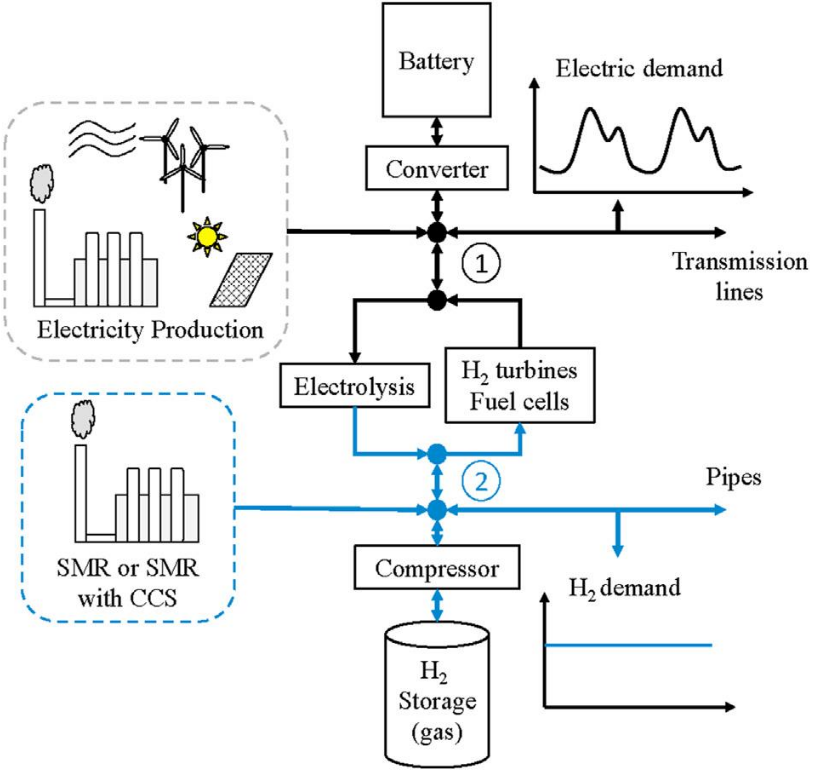
13-bus model of Texas power system [2]



Potential wind and solar sites in Texas

Source: Bødal & Korpås

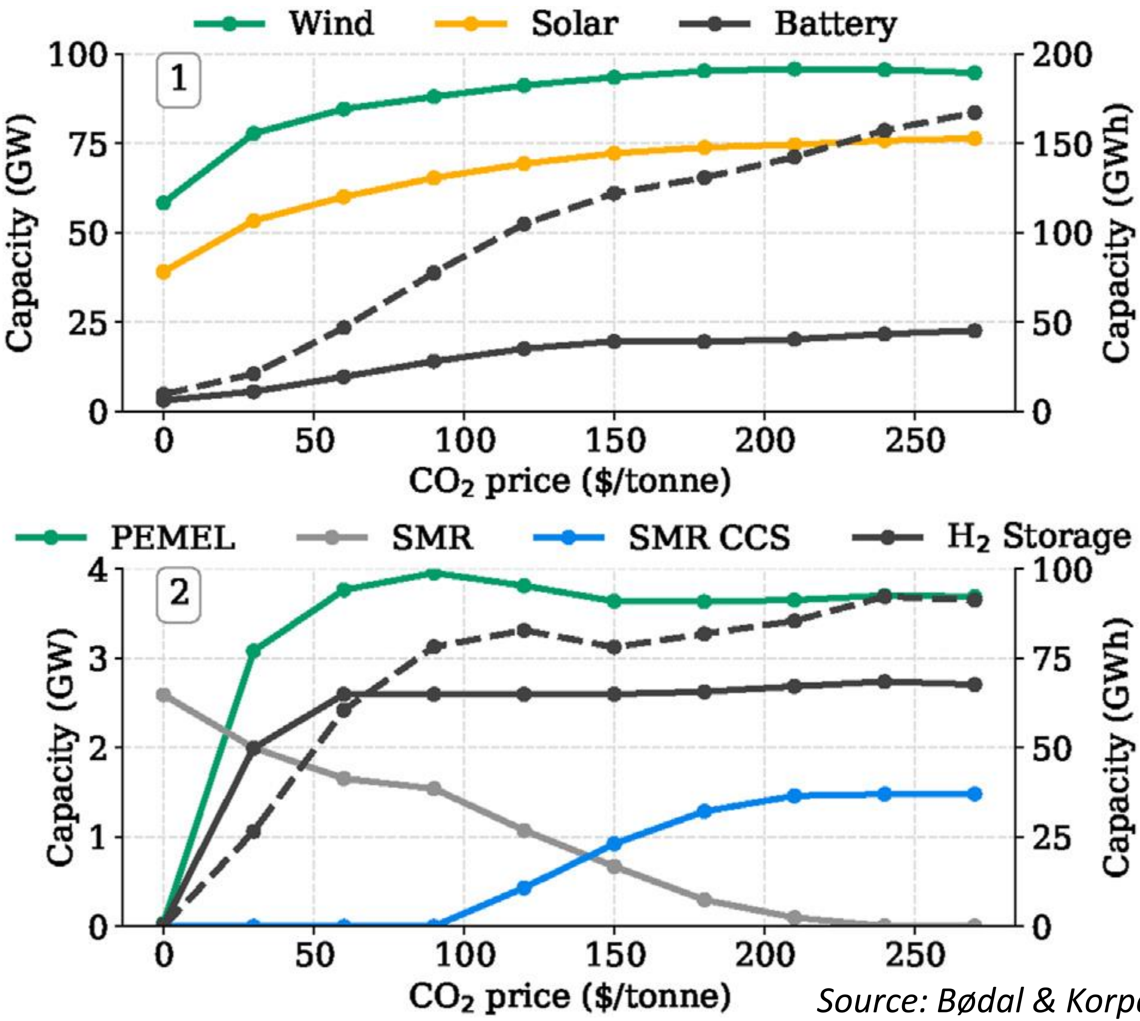
Optimization model for EL-H2 system



- Minimize sum of investment, retirement, fixed and variable operation cost
- Separate power and energy capacities of storage
- Simplified power grid and H2 grid representation
- 1 year with 1hour timestep.
- H2 demand and power demand both have VOLL cost
- Programmed in Python/Pyomo

Optimal capacity development as a function of CO2-price

- Wind and solar profitable without CO2-tax or subsidies
- Batteries and H2 substitutes gas power
- H2-ELY kicks off at low CO2-price
- H2-SMR CCS introduced above 100 $/tonne



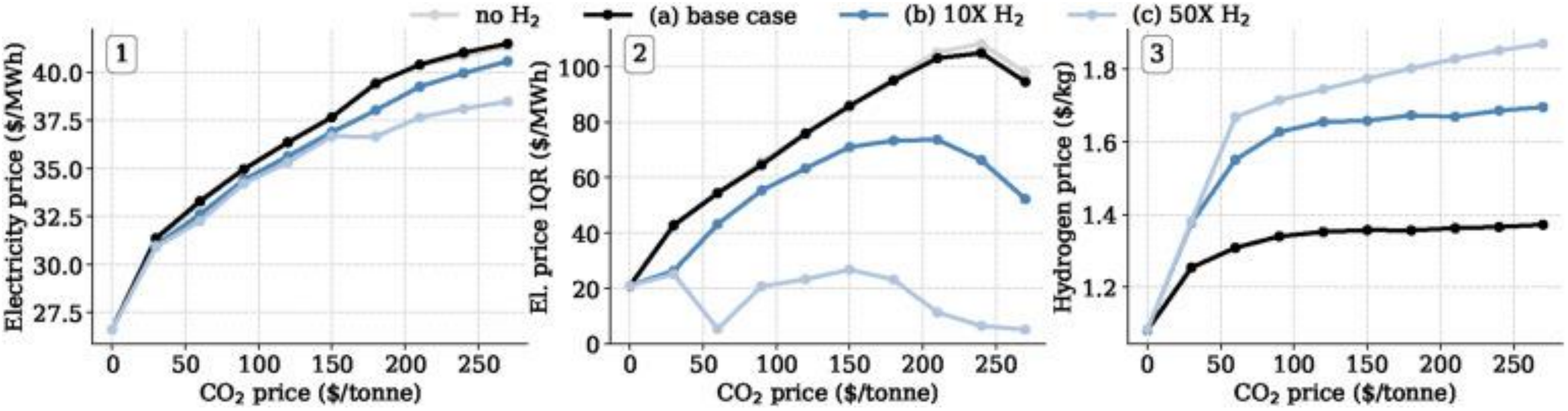
Source: Bødal & Korpås

NTNU

Interplay between electricity and H2: summary

The NTNU/MIT «Texas study»

- Hydrogen production makes wind and solar more profitable
- Flexible H2 production is beneficial for the power grid
- Flexible H2 production reduces price variations
- Large-scale, flexible H2 production *together with* new wind and solar can reduce the cost of electricity
  - *The lower electricity price for higher H_2 demands can be explained by the mitigation of large amounts of battery and transmission capacity that otherwise would have been needed to integrate significant amounts of VRE electricity generation at high CO_2 prices.*

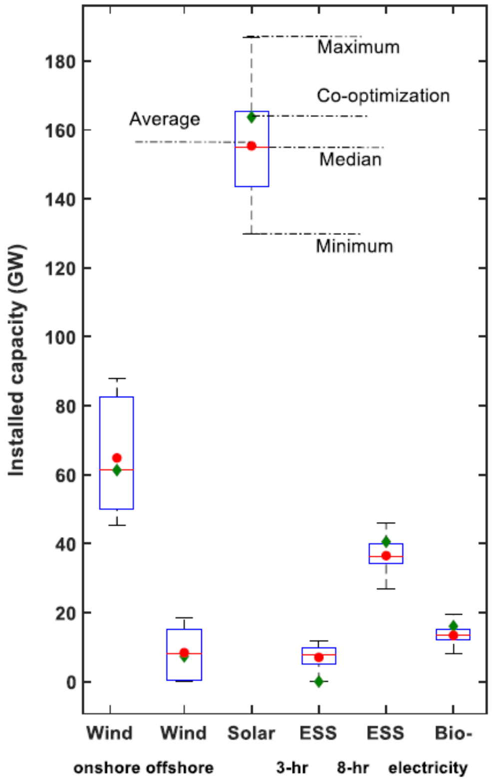


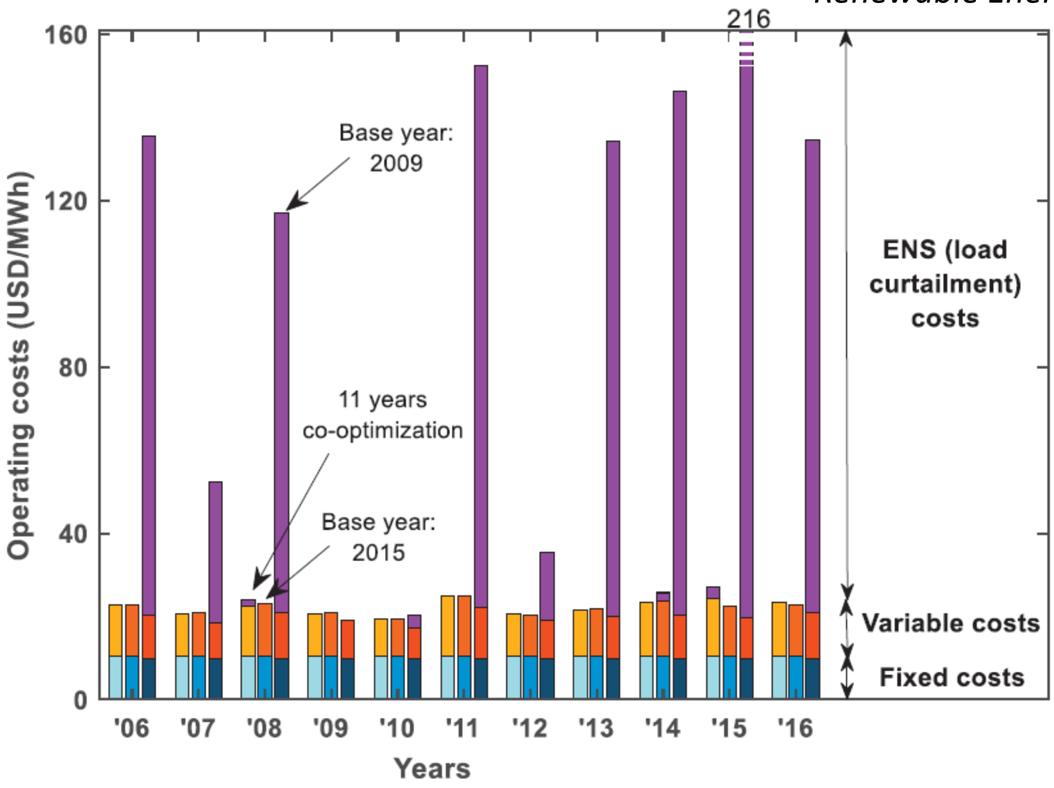
Impact of batteries for optimal RES-mix

(Jafari, Korpås, Botterud 2021)

Annual wind and solar variations must be accounted for in CEP

(Jafari, Korpås, Botterud, Renewable Energy, Aug. 2020)





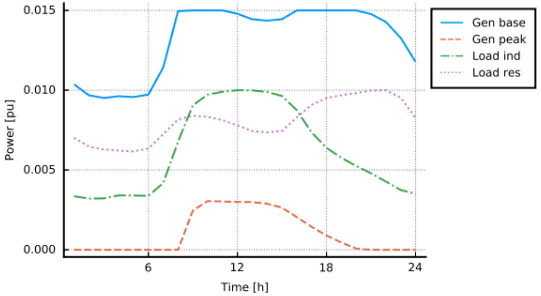
Resources in Zero-carbon electricity systems

	Zero Fuel Cost	Non-Zero Fuel Cost
Non-Zero Marginal Cost	(Opportunity Cost) Reservoir hydro Pumped storage hydro Batteries Other Storage Demand Response	(Variable Fuel Cost) Bioenergy Hydrogen Gas w/CCS Coal w/CCS
Zero Marginal Cost	(No Opportunity Cost) Wind Solar Run-of-river Hydro Geothermal	(Fixed Fuel Cost) Nuclear

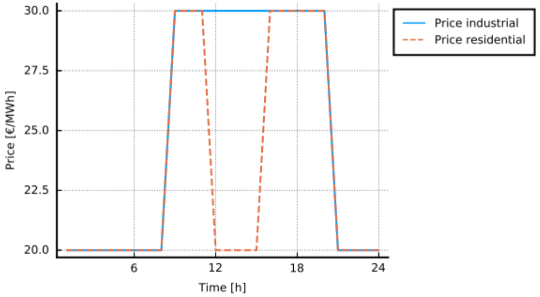
Zhou, Botterud, Levin, ANL-22/31.

- What will planning, operations and market prices look like in a zero-carbon system?

Pricing in thermal systems



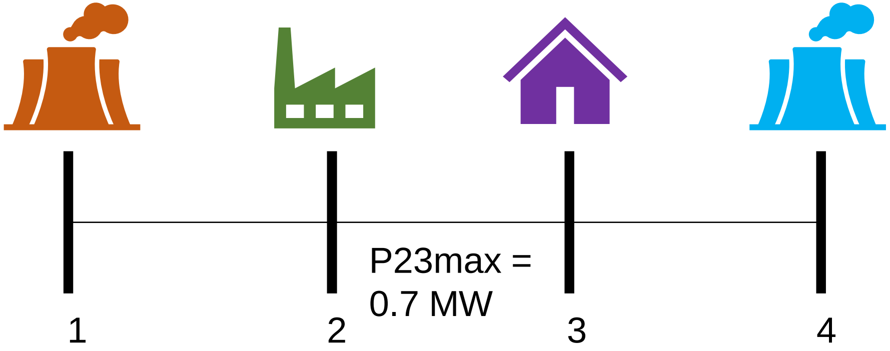
(a) Load and generation.



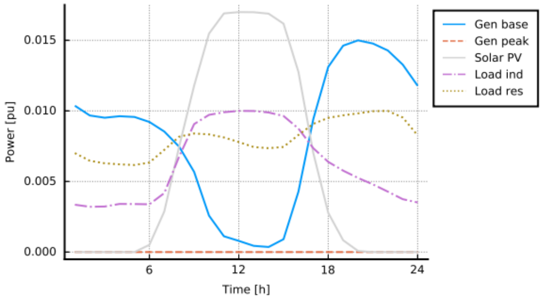
(b) System LMP.

Peaker
MC = 30 €/MWh
Pmax = 0.5 MW

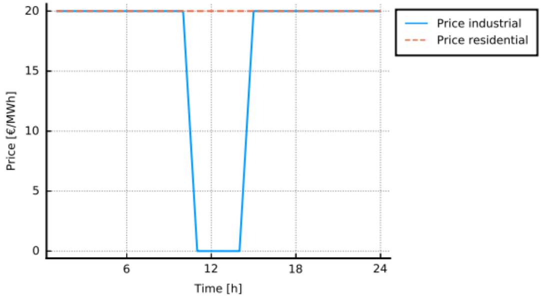
Baseload
MC = 20 €/MWh
Pmax = 1.5 MW



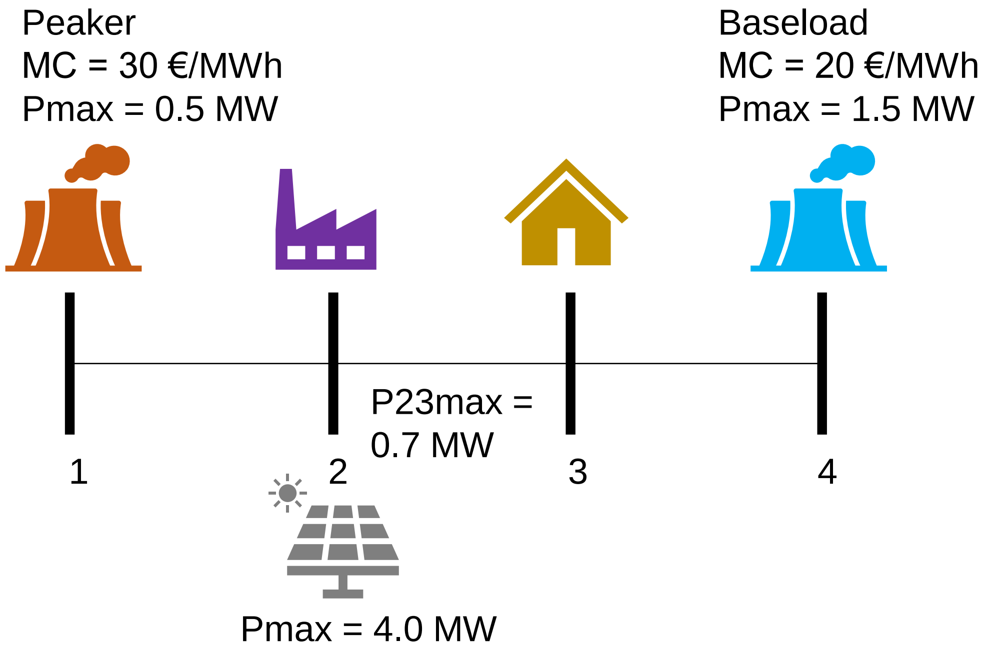
Pricing with variable renewable energy sources (VRES)



(a) Load and generation.

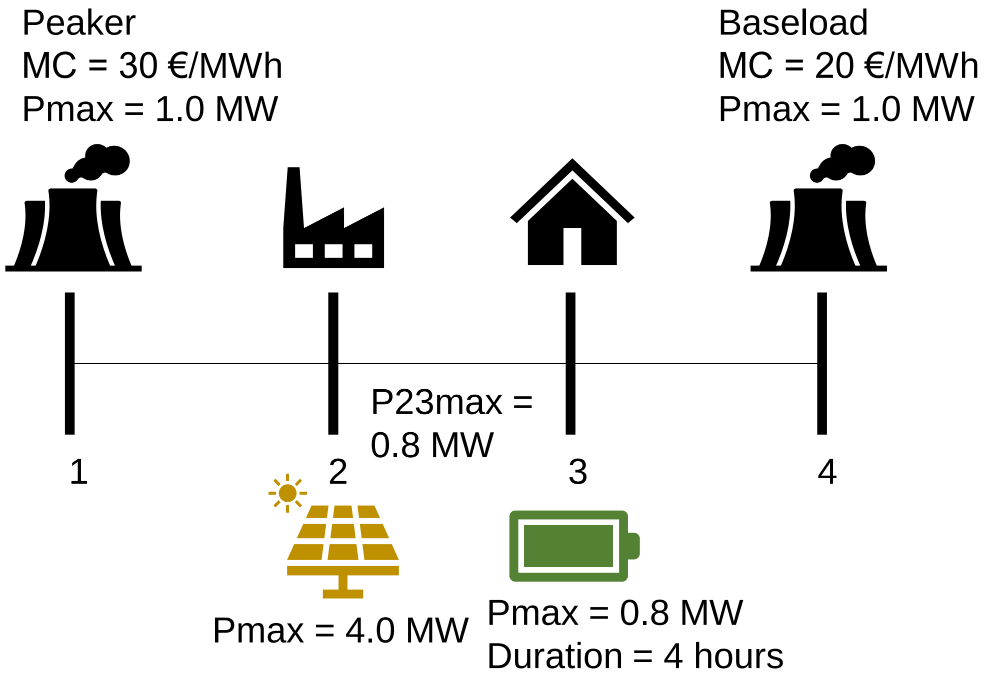


(b) System LMP.



Pricing with energy storage systems (ESS)

?

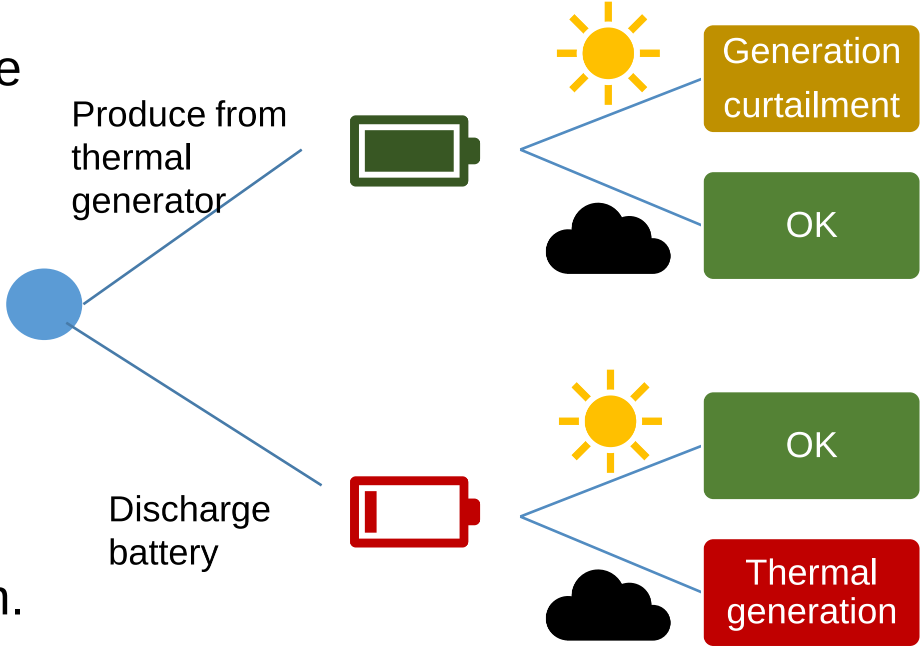


Marginal value pricing

- The price is set by the marginal cost/value of the marginal unit.
- The marginal value of an ESS (battery) represents its future opportunity value. How much is the stored energy worth in the future if it is dispatched perfectly?
- Can be determined through optimization. But…

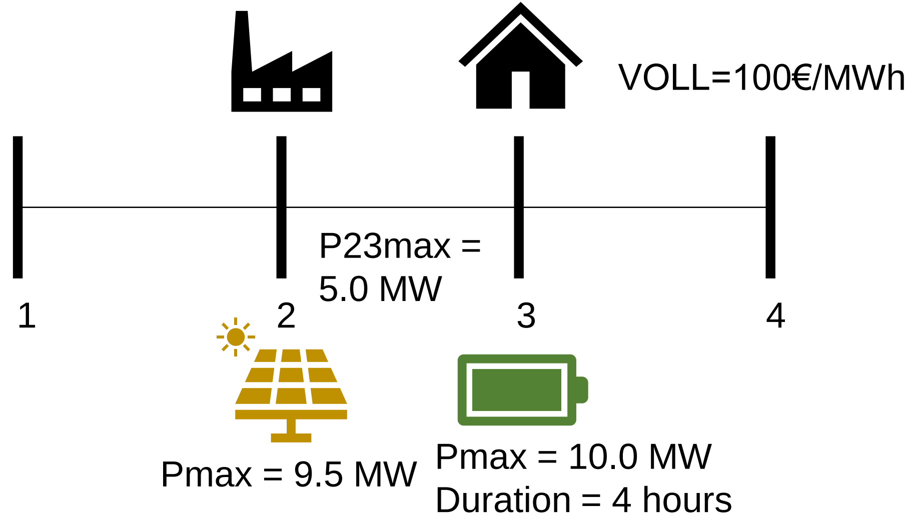
Decisions and uncertainty

- Uncertainty influences the future decisions and the marginal value. The costs for best and worst case are not symmetric.
- The decisions are not taken at once, but stagewise. The marginal value is not only time dependent, but also state dependent.
- Stored energy has a value beyond the optimization horizon.
  - Similar to hydropower planning



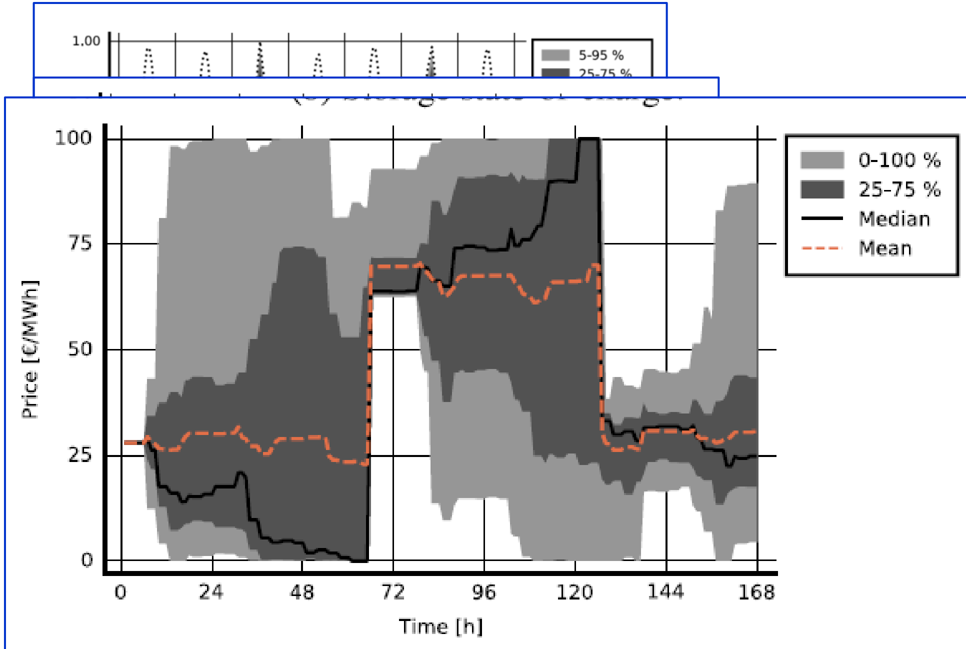
Pricing with only VRES and ESS

- What sets the price when there is no thermal generation?



Pricing with only VRES and EES

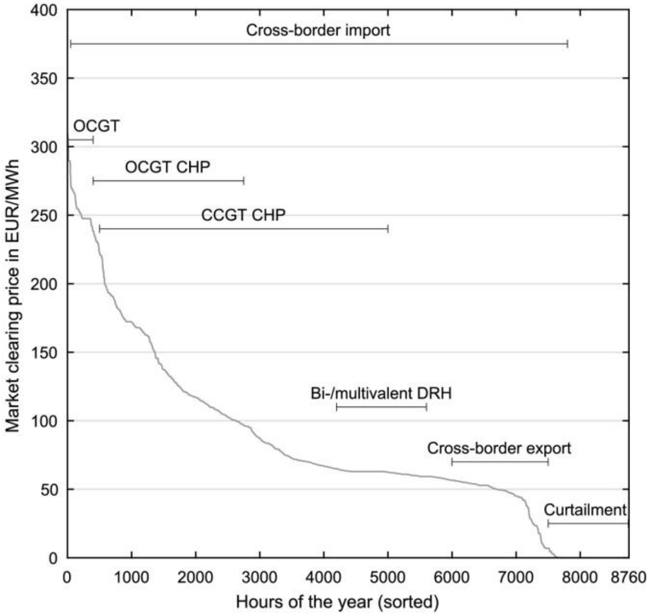
- When ESSs replace some of dispatchable capacity, scarcity may occur when the SOC is low. Load shedding becomes the marginal unit.
- The marginal cost is influenced by the scarcity price, which becomes effective without scarcity necessarily occuring. The price signal can prevent scarcity.
- Creates opportunities for:
  - flexible loads with marginal cost below scarcity price.
  - More ESSs.



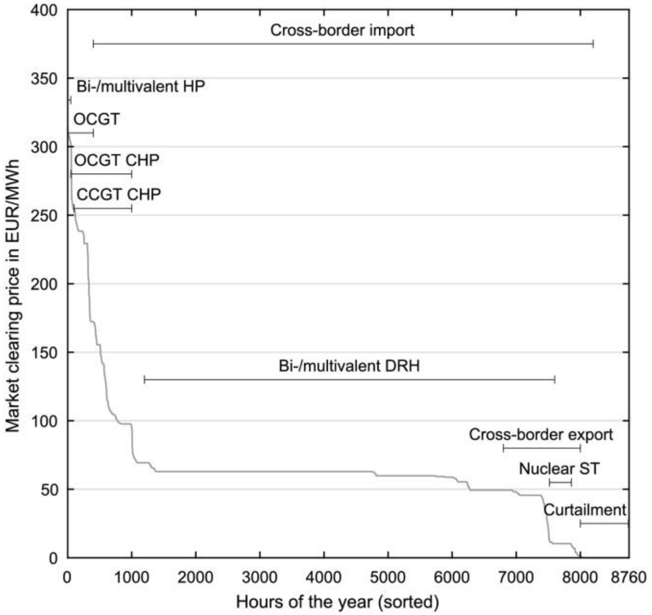
(d) LMP at residential bus.

Demand-side flexibility can be significant

Demystifying low-carbon electricity market clearing



(a) DEU market area (significant cross-border exchange)

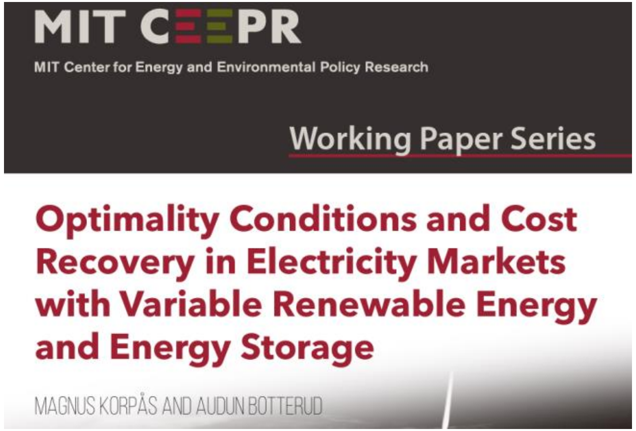


(b) FIN market area (limited cross-border exchange)

Härtel, Korpås (2020)
https://doi.org/10.1016/j.eneco.2020.105051

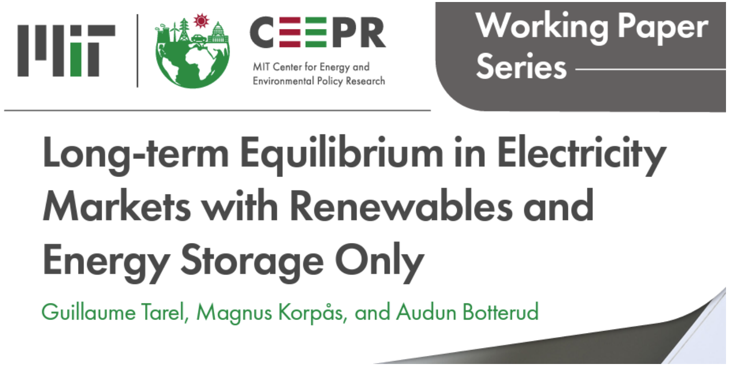
Long-term Equilibrium in Low Carbon Markets: Analytical Insights

Can current electricity market structures provide adequate incentives for investment in future low-/zero-carbon power systems?


MIT CEEPR
MIT Center for Energy and Environmental Policy Research
Working Paper Series
Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage
MAGNUS KORPÅS AND AUDUN BOTTERUD

WP 2020-005

VRE, Storage, and Thermal can co-exist in an energy-only market with prices based on short-term costs.


MIT CEEPR
MIT Center for Energy and Environmental Policy Research
Working Paper Series
Long-term Equilibrium in Electricity Markets with Renewables and Energy Storage Only
Guillaume Tarel, Magnus Korpås, and Audun Botterud

(Published in *Energy Systems*, 2024) WP 2022-012

Equilibrium prices now include a term representing capital costs. That is not aligned with current market structures.