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Renewables and Flexibility in Modern Energy Systems

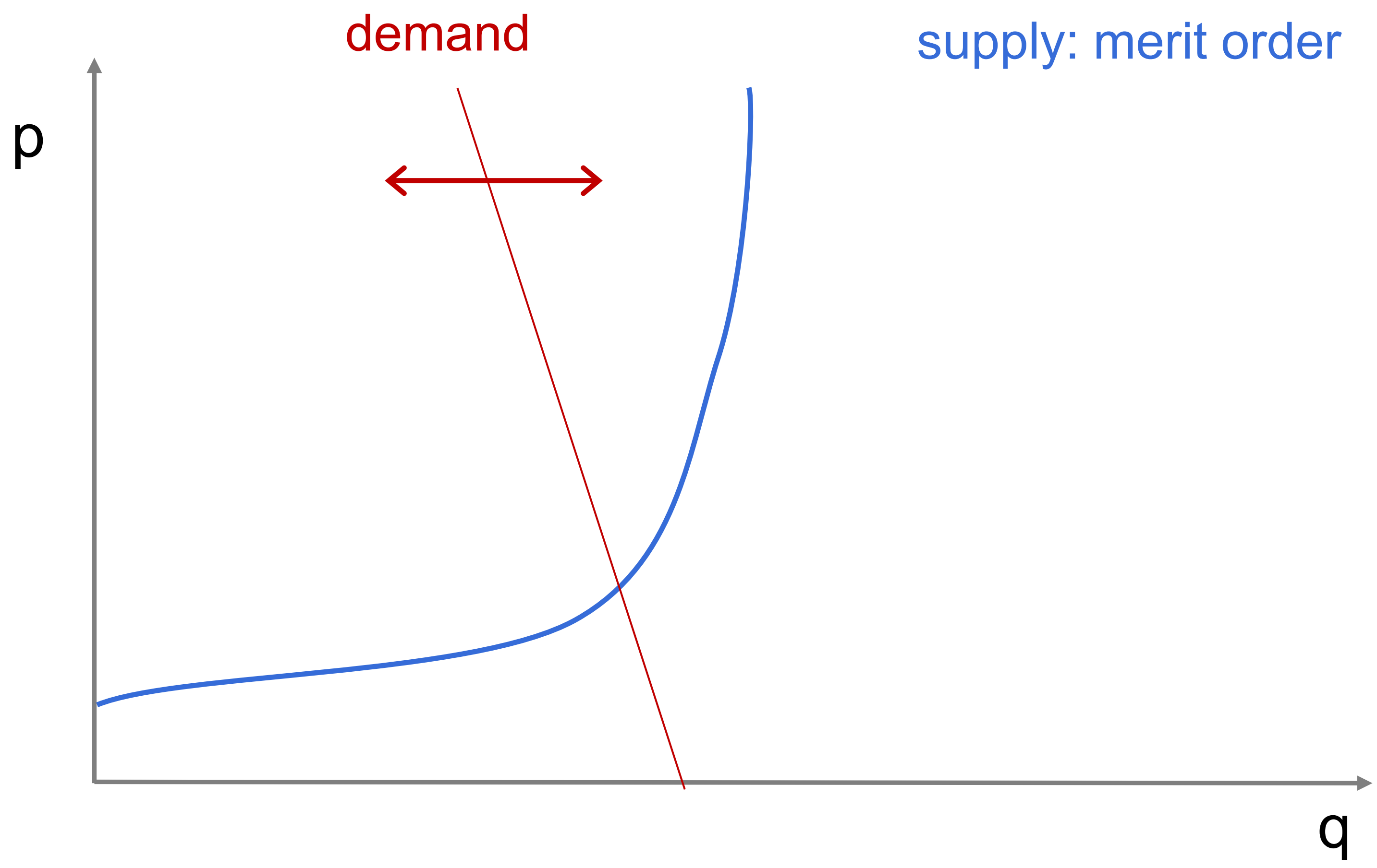
Prof. Dr. Felix Müsgens

@

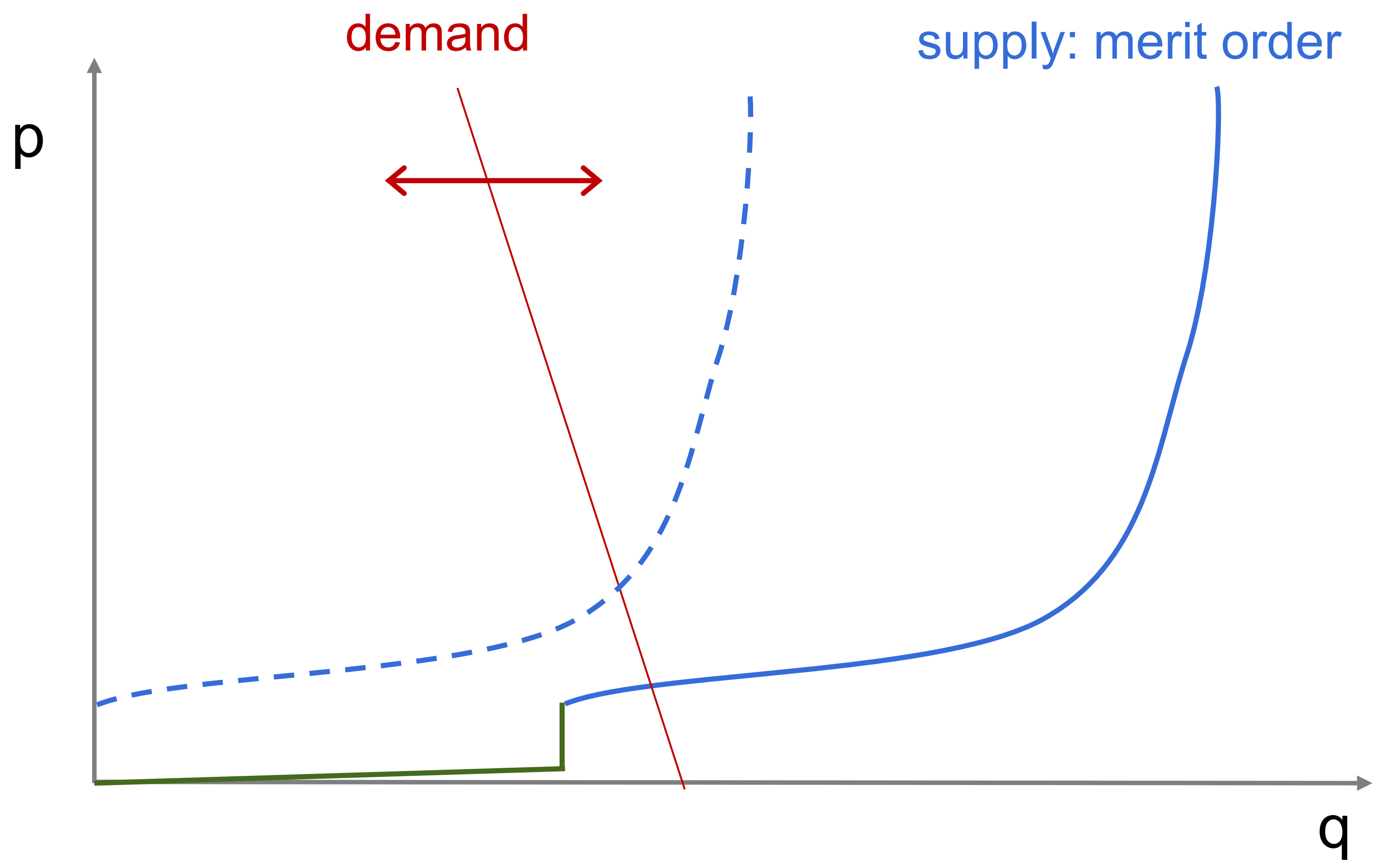
Enerday

Dresden, 4th of April 2025

Old: No Renewable Generation



Now: Renewable Generation is Added



Fallacy 1: Adding RES-capacity (with low variable cost) lowers the average wholesale price.

Fallacy 1: ~~Adding RES-capacity (with low variable cost) lowers the average wholesale price~~.

Correct:

- Fixed costs for both RES and back-up capacity are covered in equilibrium.
- Under certain conditions, the average price remains exactly the same.

See

- Wissen, R., Nicolosi, M. (2008): Anmerkungen zur aktuellen Diskussion zum Merit-Order-Effekt der erneuerbaren Energien, *Energiewirtschaftliche Tagesfragen* 58, 110–115.
- Antweiler, W., Müsgens, F. (2021): On the Long-Term Merit Order Effect of Renewable Energies, *Energy Economics*, Vol. 99, 105275. doi: 10.1016/j.eneco.2021.105275.

Future Equilibrium: Conventional System has Adjusted

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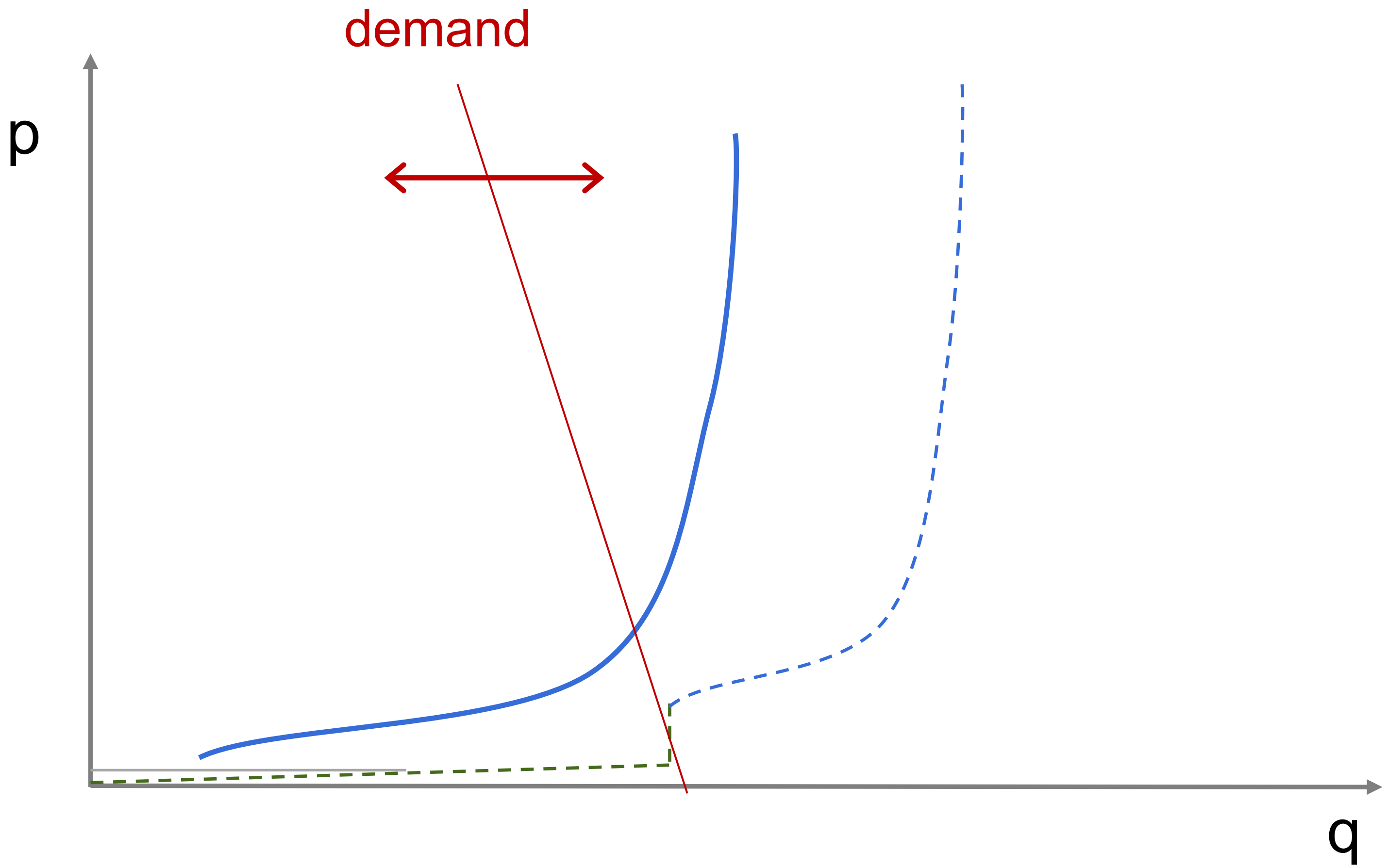

Now we understand the pitfalls of fallacy 1…

… let's move on to…

Fallacy 2: So prices will be very low (zero) during most hours of the year and extremely high (spikes) during the remaining few hours?

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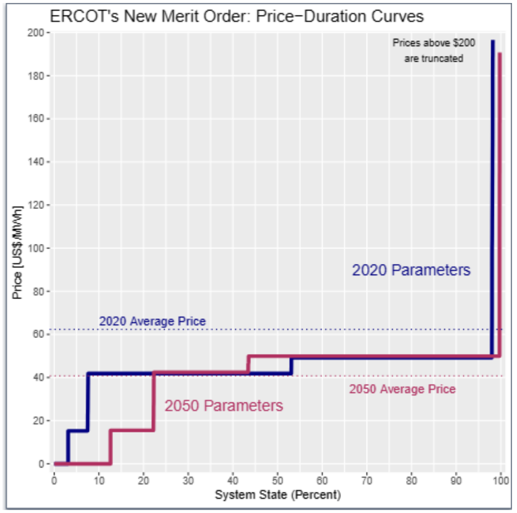

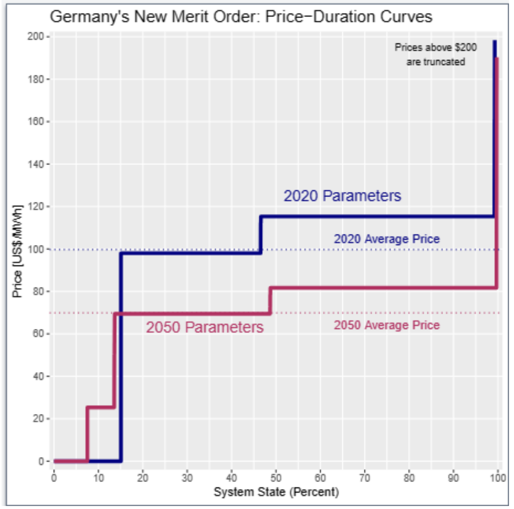

See

This presentation ☺ (based on Antweiler, W., Müsgens, F. (2025): The New Merit Order: The Viability of Energy-Only Electricity Markets With Only Intermittent Renewable Energy Sources and Grid-Scale Storage, *Energy Economics, https://www.sciencedirect.com/science/article/pii/S0140988325002634*)

Energy Transition in the Long Run

- The electricity grid of the future will move increasingly towards renewable energy (RES) and energy storage resources (storage). **How will electricity prices in a 100%-RES system look like?**
- The old merit order was defined by marginal cost steps of generators. But RES and storage have (near-) zero marginal costs. What prices will emerge? Could Energy Only Markets (EOM) still work?

What we Do

1. Develop a simplified algebraic model of the ‘new merit order’
   - with a single RES and single storage technology, linear model
   - super-simple model: get intuition
   - extend to a model with two types of storages (battery + hydrogen)
2. Develop a general theoretical model
   - Increase validity of analytical results by making them more realistic
   - Foundation for empirical analysis
3. Analyze the ‘new merit order’ empirically in two different locations
   - Texas (ERCOT)
   - Germany

   and identify optimal composition of RES + storage (with two types of RES and two types of storage) and simulate cost scenarios 2020–2050.

The Simple Model

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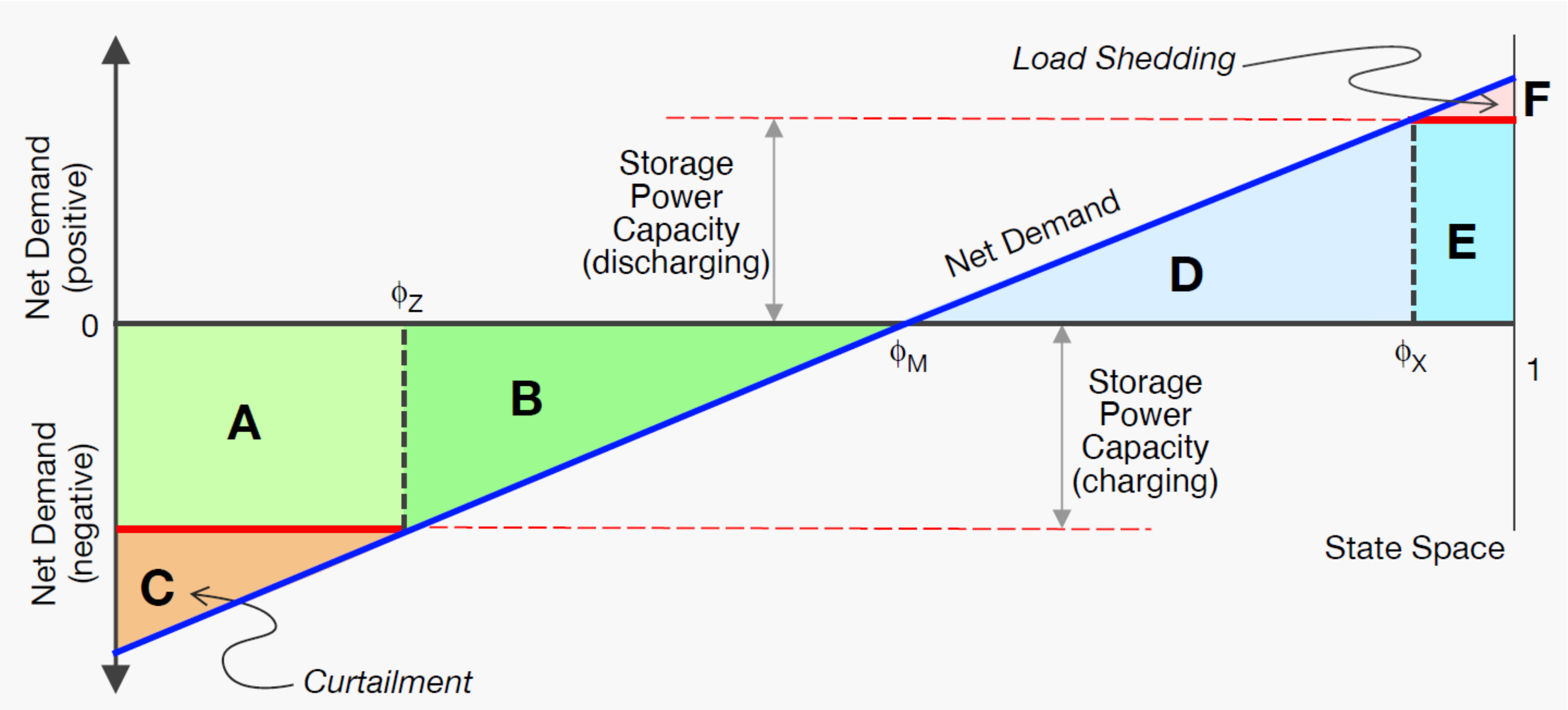
- **Purpose**: tease out economic intuition
- **Method**: simplify as much as possible, introduce strong assumptions
- **Results**: clear & meaningful analytic expressions
- **Caveat**: not suitable for empirical work; we develop a general theoretical model in the next section for this purpose

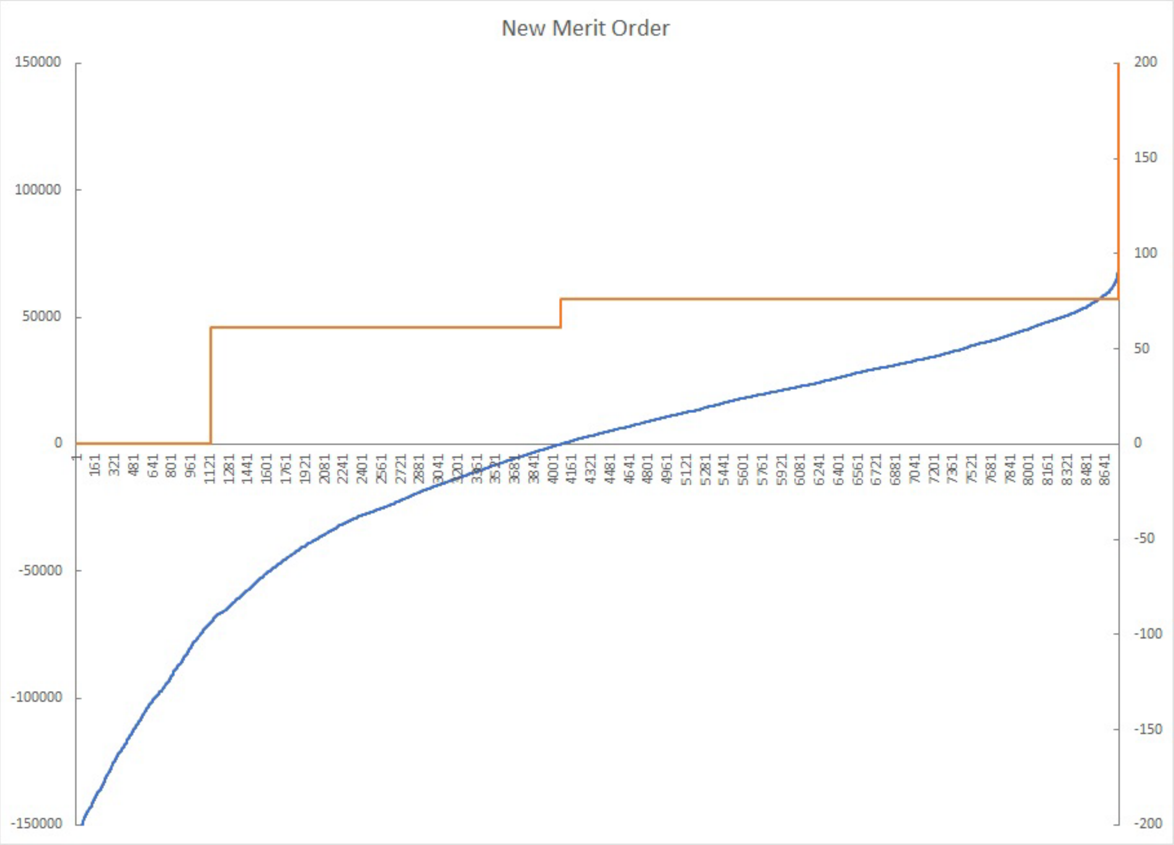
Discussion of the Intuition



Interpretation

- Four price ranges emerge
  - When RES is curtailed, prices are zero. Storage charging at maximum.
  - When storage is charging partially, price is ηp.
  - When storage is discharging partially, price is p.
  - When load is shed, prices are ω. Storage discharging at maximum.
- Key issues to consider:
  - Free entry eliminates arbitrage benefits for storage in the partial-load region (storage indifferent between producing and not producing).
  - Storage must cover its fixed cost from charging sometimes at zero prices and discharging at VOLL.
  - Both curtailment periods and peak price periods are necessary.
  - RES covers its fixed cost when prices are at ηp, p, which is most of the time, and ω during peak demand periods.

Residual Load and Optimal Prices with simple configuration



- 1 RES
- 1 Storage
- Storage losses (round-trip efficiency: 80%),
- Model is linear with VOLL at 20.000 USD/MWh
- Curtailment free of charge

Insights from Generalisation

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- **Purpose**:
  - Develop a foundation for our empirical work
  - More robust theoretical considerations
- **Method**: introduce richer structure (two types of renewables, two types of storage, demand response)
- **Calibration**: use two data sets from different jurisdictions; calibrate to 2020 and 2050 cost parameters.
- **Results**: empirical insights into capacity composition and the resulting 'new merit order' of equilibrium prices.

Demand, Supply and Price

- Demand q follows a distribution $q \sim Q$, we refer to this demand as „latent demand“, i.e. demand at a price of 0 USD/MWh
- Price p is defined with the inverse demand function $p = \theta\ (q - x + z) \geq 0$, where
  - x is available supply and
  - z is potential curtailment of RES
- Available supply $x = x_V + x_W + x_B + x_H \equiv v\bar{x}_V + w\bar{x}_W + b\bar{x}_B + h\bar{x}_H$, where
  - V, W, B, H represent RES (photo**V**oltaics and **W**ind) as well as storage (**B**attery and **H**ydrogen)
  - maximal output is constrained by installed capacities $\bar{x}_i$ for each technology i
  - RES utilization rates $v \equiv x_V/\bar{x}_V \in [0,1]$ and $w \equiv x_W/\bar{x}_W \in [0,1]$ follow empirical distributions $v \sim \mathcal{V}$ and $w \sim \mathcal{W}$, while storage utilization is determined endogenously and between $[-1,1]$
  - Investment costs for technology i are f_i, all variable costs are zero

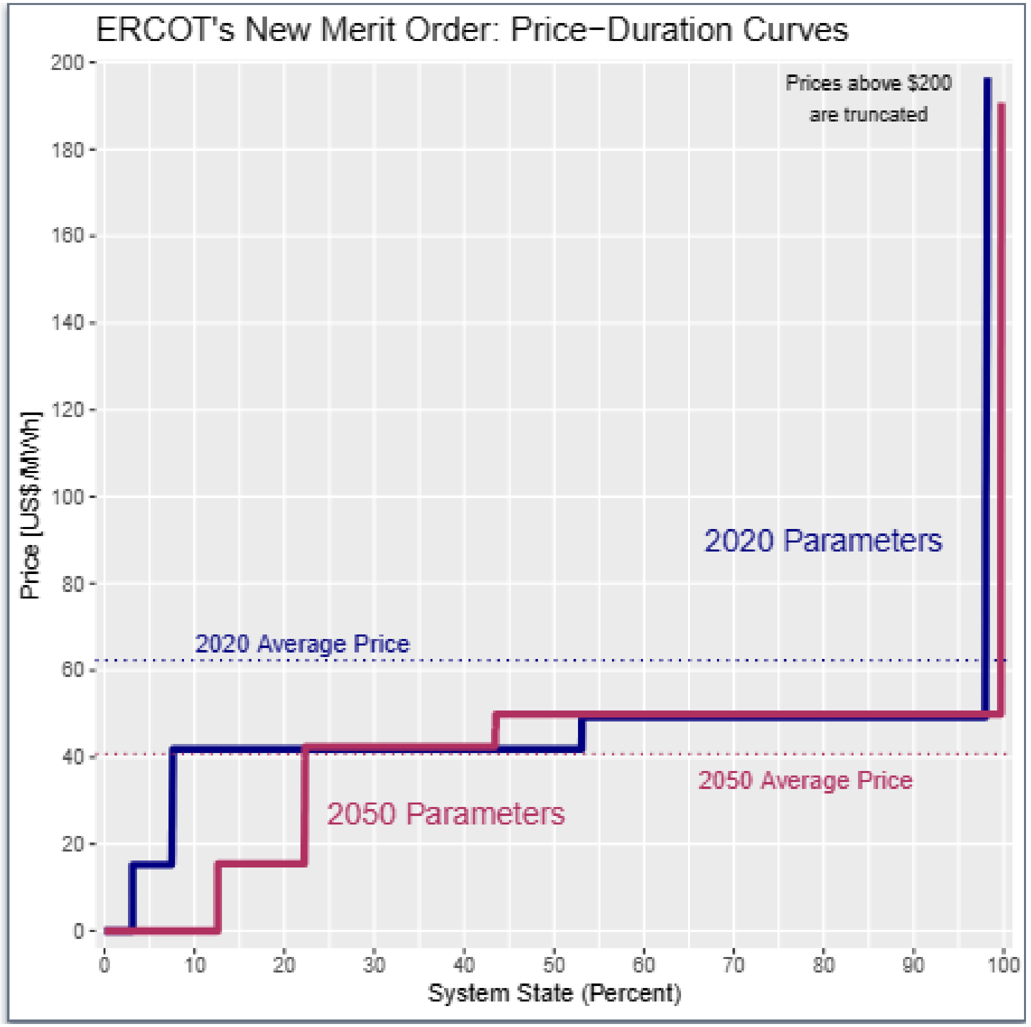
The Stochastic Set-up

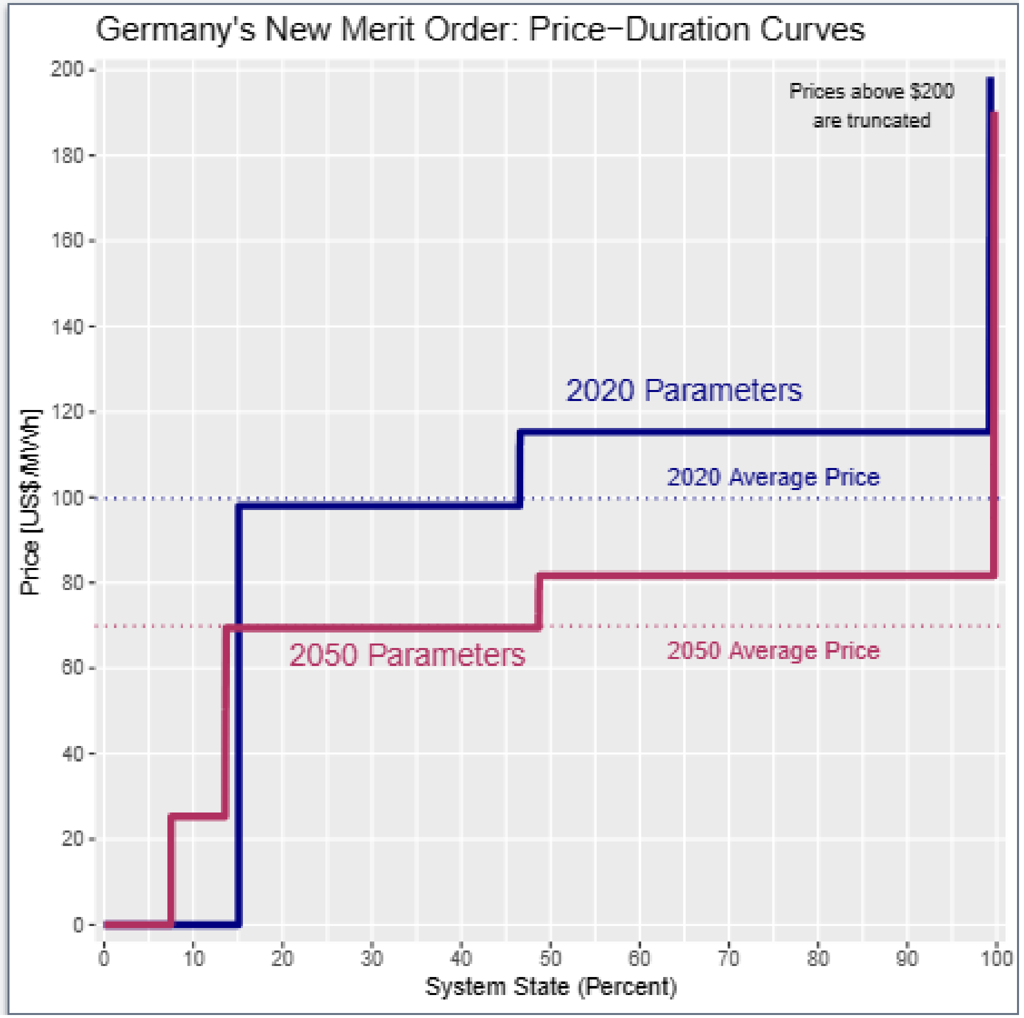
- The correlation pattern between $Q, \mathcal{V}, \mathcal{W}$ can be arbitrarily complex. It is useful to describe this empirical relationship through a probability function $\Phi(q, v, w)$: $\iiint \Phi(q, v, w) dq\, dv\, dw = 1$, for which we introduce a simplified notation $\phi(y) \equiv \iiint \Phi(q, v, w) y\, dq\, dv\, dw$.
- Storage production must be balanced: $\eta_S\, \phi(\max\{0, -s\})\bar{x}_S = \phi(\max\{0, s\})\bar{x}_S$

The Welfare Maximization

- Social welfare in our system is: $W = \theta q^2/2 - \sum_i f_i \bar{x}_i - \frac{\Phi(p(\bar{x})^2)}{2\theta}$
- First order conditions for welfare maximization specify
  - $\frac{dW}{d\bar{x}_i} = f_i - \Phi\left(p \frac{dx}{d\bar{x}_i}\right) = 0$, which exactly specifies the zero profit conditions, for example:
    - $\frac{dW}{d\bar{x}_V} = f_V - \Phi(v \cdot p(\bar{x})) = 0$, where $\bar{x}$ is the vector of installed capacities
    - …
  - $\Phi(p) = \Phi(q) - \Phi(v)\bar{x}_V - \Phi(w)\bar{x}_W + \Phi(z)$, which can be simplified to $\bar{v}\bar{x}_V + \bar{w}\bar{x}_W - \bar{z} = \bar{q} - \bar{p}/\theta$
  - $$\Phi\left(\mathrm{con}\left(\frac{q - x_R - p^*/\theta}{\bar{x}_S}; 0, 1\right)\right)\bar{x}_S = \sum_{i \in \{B,H\}} \eta_i \Phi\left(\mathrm{con}\left(\frac{q - x_R + \underline{x}_i - \eta_i p^*/\theta)}{\bar{x}_i}; -1, 0\right)\right)\bar{x}_i$$

Empirical Analysis





Conclusion

- The ‘new merit order’ looks very much like the old merit order.
- RES curtailment is not a bug but a (necessary) feature.
- A RES + storage system looks increasingly cost-effective as innovation brings down the cost of RES and storage, especially in Texas.
- Our research shows: Energy-only markets remain viable and functional in a 100% RES world. Be in favor of capacity mechanisms if you must – but do not blame renewables for it.

Vielen Dank für die Aufmerksamkeit!

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Lehrstuhl Energiewirtschaft

https://www.b-tu.de/fg-energiewirtschaft

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Google Scholar

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Energy Economics – YouTube

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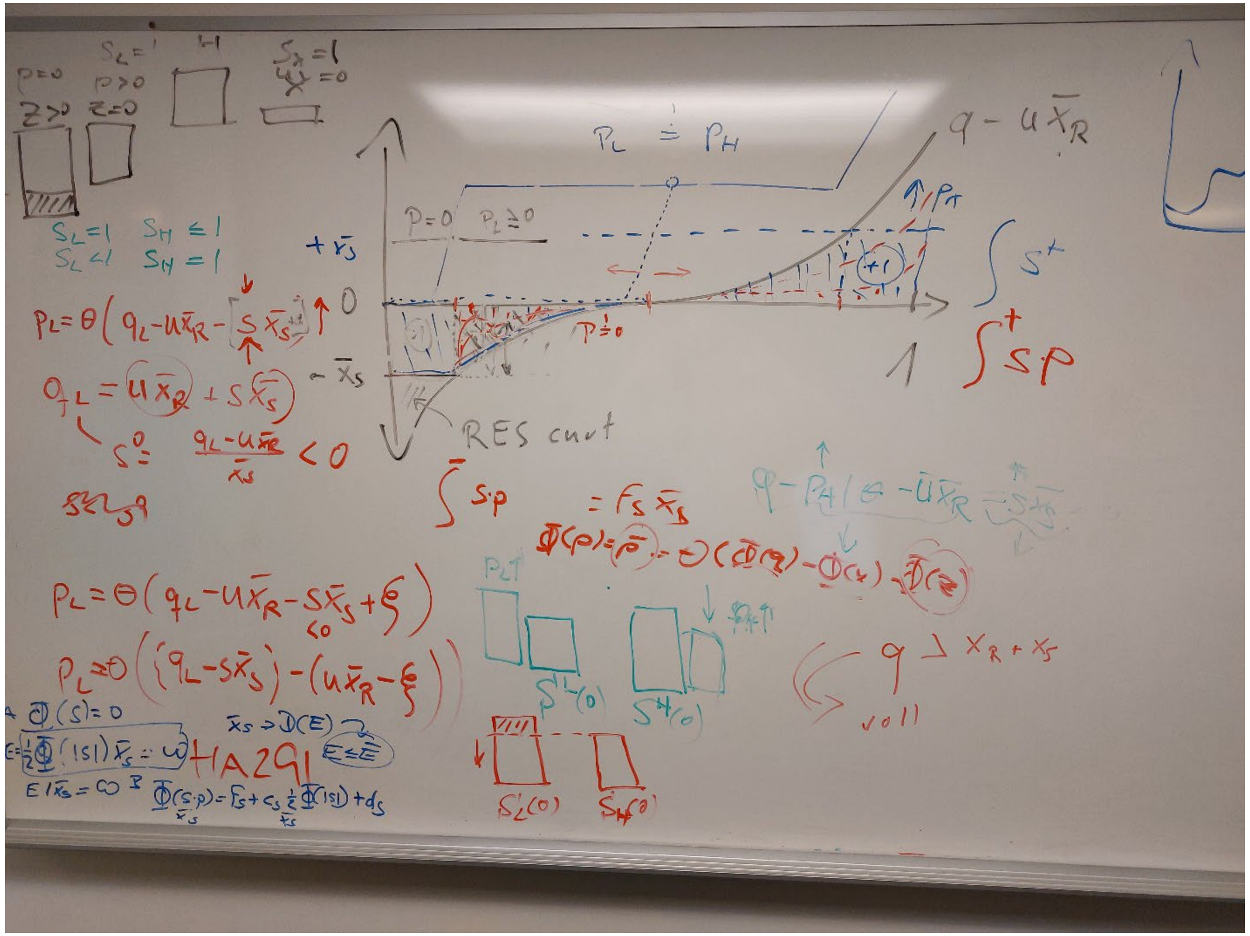
Work in Progress



How to get there

- We analyze the following research questions:
  - What happens to the merit order of electricity markets when all electricity is supplied by intermittent renewable energy sources coupled with large-scale electricity storage?
  - With near-zero marginal cost of production, will there still be a role for an energy-only electricity market?
- We develop
  - stylized analytical models and
  - analyze the electricity markets in Texas and Germany empirically.
- Our work demonstrates that as long as free entry and competition ensure effective price setting, an efficient new merit order emerges in electricity markets even when the grid is completely powered by intermittent sources with near-zero marginal costs. We find that energy-only markets remain viable and functional.

Stylized Analytical Model

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- We consider two analytical models
  - General model (non-linear)
    - price responsive demand
    - various renewable and storage techs
    - stochastic demand and stochastic supply from RES
    - demand and production from various RES can be correlated
    - can be solved numerically
  - Simplified model (linear)
    - inelastic demand + value of lost load
    - one RES technology (R) and one storage (S)
    - demand and RES generation are stochastic (and uncorrelated)
    - can be solved analytically

- Solving this set-up for an exemplary system (Texas ERCOT, solar and wind, li-ion battery and hydrogen, cost parameters 2020 and 2050) reveals: