Electricity Markets in a Fully Decarbonized Economy

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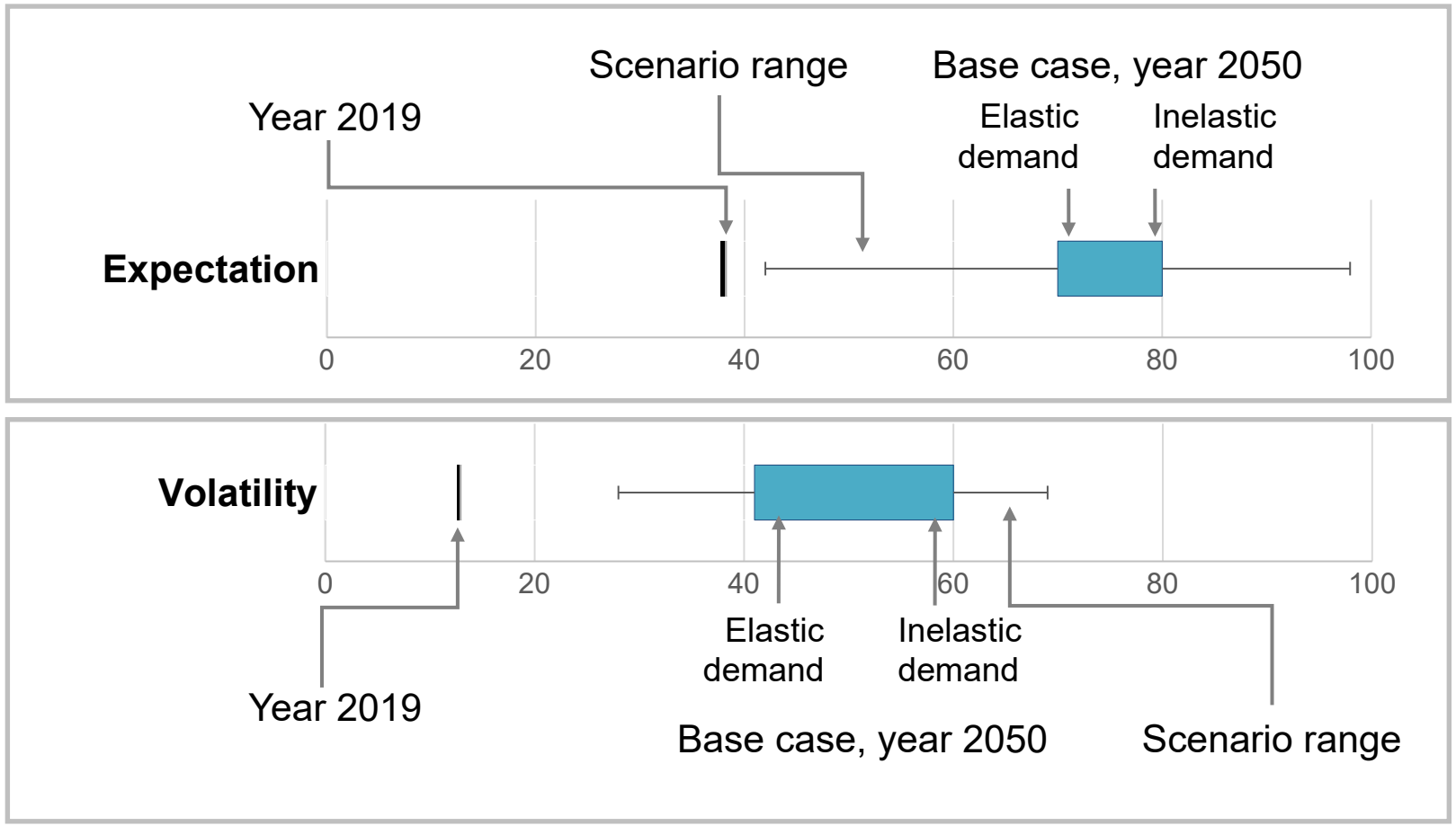
Also in a fully decarbonized economy, the day-ahead market for electricity continues to function, with higher prices and higher volatility than today

Executive summary

- There is concern that the merit order effect (i.e., low power prices due to renewable power) makes energy-only power markets in fully decarbonized economies impossible
- We can show that this effect is counter-balanced, and that the average electricity price as well as the volatility actually increases
- Starting with studies on energy transition, we apply a novel approach by modeling the supply and demand separately, with periodic, mean-reverting stochastic processes
- The model is computationally efficient – the implementation leads to less than one hour of computation for > 50 scenarios, on standard hardware

Under a wide range of assumptions, we can show that the merit order effect is counter-balanced; average electricity price and volatility increases

Day-ahead market, in € / MWh



- Demand elasticity dampens both average price increase and volatility increase
- Volatility defined as the standard deviation of the de-trended time series

Source: own calculations, compare with Grimm-Policy-Brief-CD-FINAL.pdf (utn.de), see, e.g., faz.net or spiegel.de, 10 April 2024

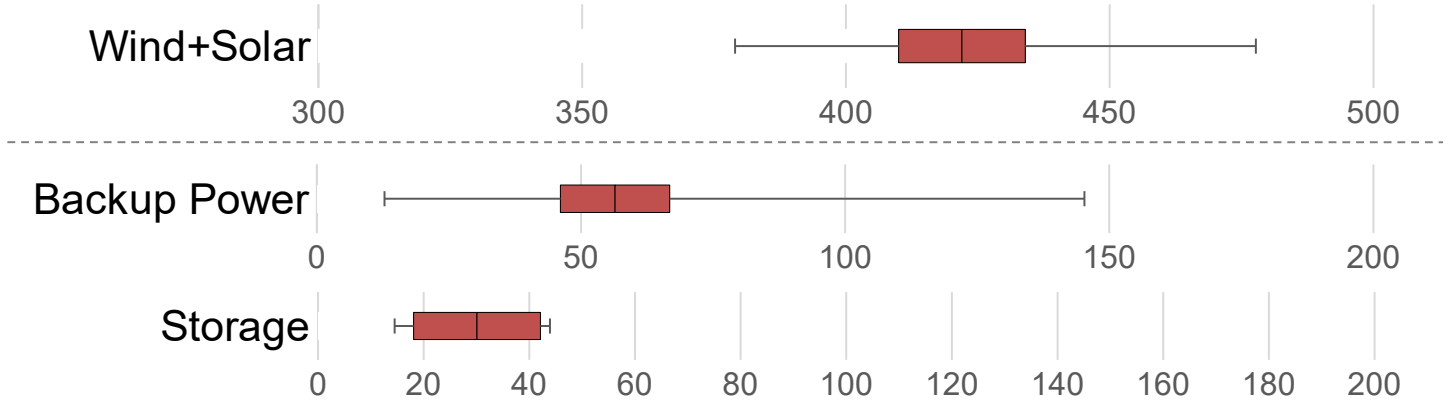
Current studies on energy transition agree on certain characteristics of a future electricity system, and provide a wide range of different scenarios

Approach (1/3)

Commonalities (Extract)

- Most power is generated by wind power (onshore and offshore) and photovoltaic (PV), accompanied by storage and backup power
- For backup power, mostly green hydrogen is re-electrified
- The main scenarios in the studies assume that most of the economy is electrified

Estimates, in GW (Extract)



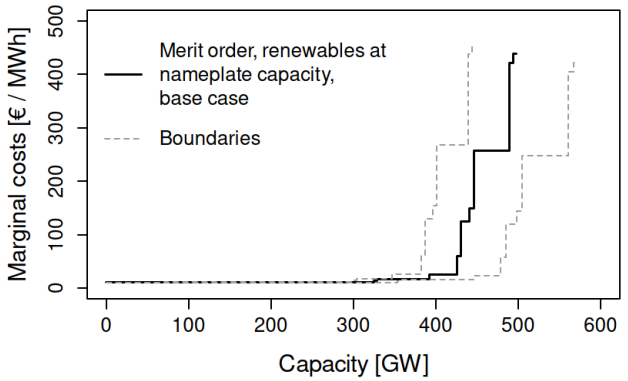
Source: [5], [6], [7], [12], [14], own calculations

We leverage this knowledge by we model the complete supply and demand separately, with renewable power on the supply side, at positive costs

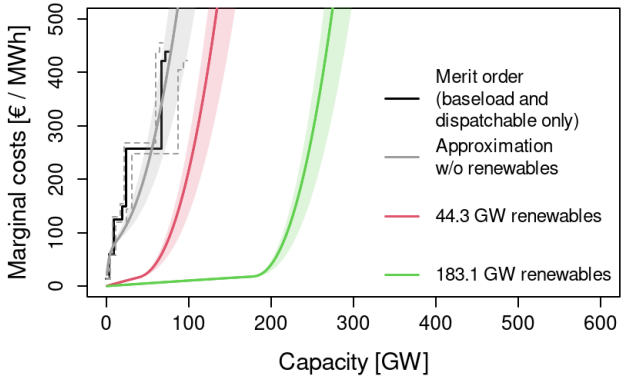
Approach (2/3)

Supply

Renewables at nameplate rating: supply curve starts flat, then steep increase



Renewables as stochastic process: present whenever wind and sun available

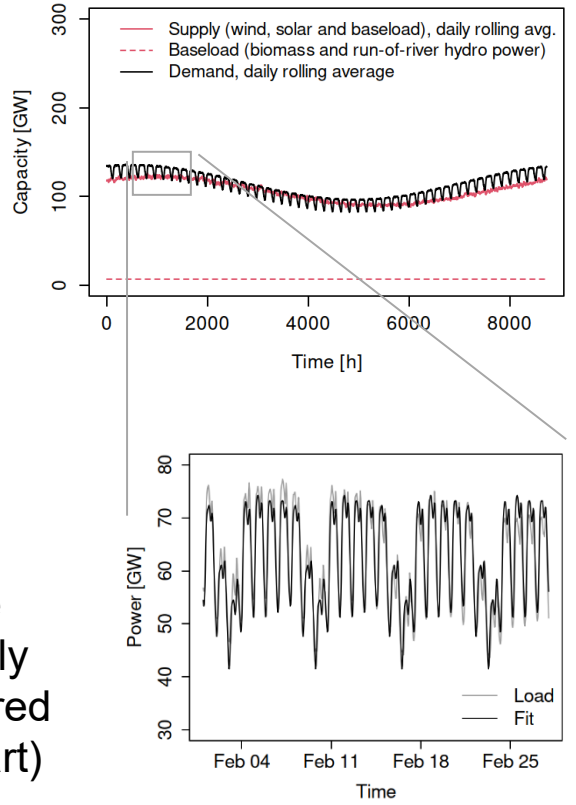


Demand

Increase determined by degree of electrification

Stronger seasonal pattern driven by electric heating

Mix of wind and solar determines how well the seasonal cycles of supply and demand align (see red and black line in top chart)



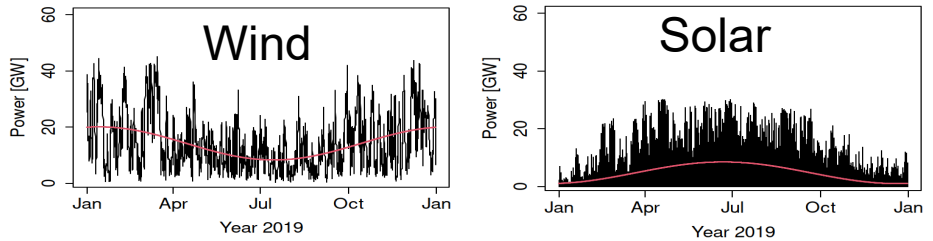
Source: [2], [3], [4], [5], [6], [7], [8], [12], [14], own calculations

The stochastic components are modelled with mean-reverting processes with positive dynamics, the price is a function of supply and demand

Approach (3/3)

Renewable power supply

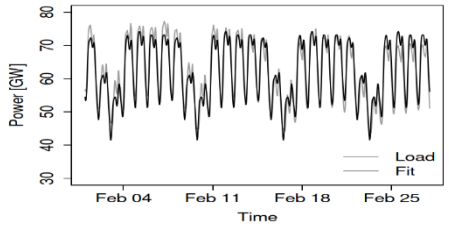
$$dX_t = \Theta\left(\mu(t) - X_t\right)dt + \sigma X_t dW_t$$



Red line: trend

Total demand

$$dY_t = \Theta\left(\mu(t) - Y_t\right)dt + \sigma Y_t dW_t$$



X_t and Y_t are Inverse Gamma distributed

σ is a function of standard deviation, expectation and time such that the Inverse Gamma distribution matches the desired distribution parameters

Electricity price

$$S = F\left(X_t, Y_t, t\right)$$

- F represents the dispatchable and intermittent supply, …
- … and it develops over time to model the system transition
- The numerical computation is efficient – standard hardware can run a high number of scenarios

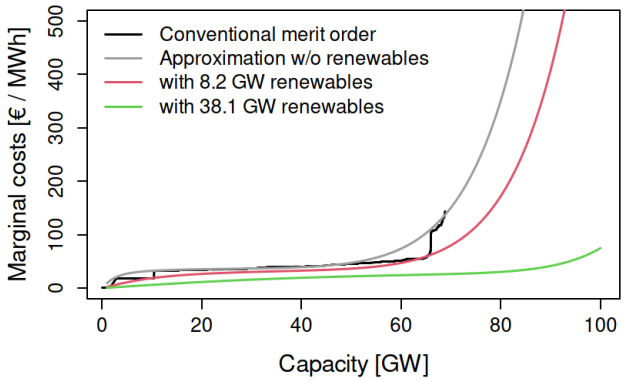
Source: [1], [2], [4], [5], [6], [7], [9], [10], [11], [12], [14], own adaptions and extensions, own calculations

Any future supply curve combines renewables with storage and backup power – this counters the merit order effect and increases volatility

Specific result #1: merit order effect, volatility

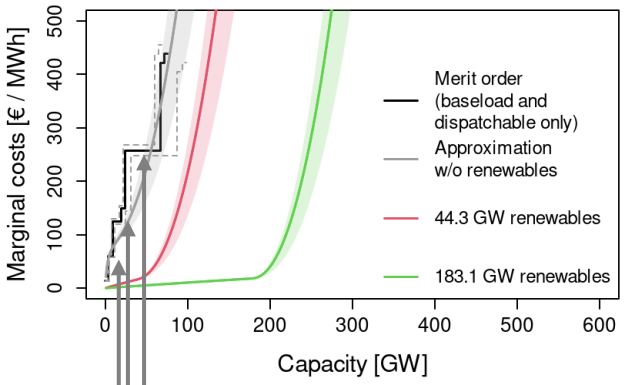
Supply curve … in base year …

- Dispatchable and baseload power with moderate slope
- Low-cost renewables not yet main source of electricity



… in the future

- Dispatchable and baseload power with steep slope
- Low-cost renewables is main source of electricity



Batteries available for dispatch, at marginal utility[1)]
Pumped hydro storage

Backup power: re-electrification of green hydrogen

- The future average electricity price is a mix of low-cost renewables with high-cost storage and backup
- Due to the steeper increase, the volatility increases as well

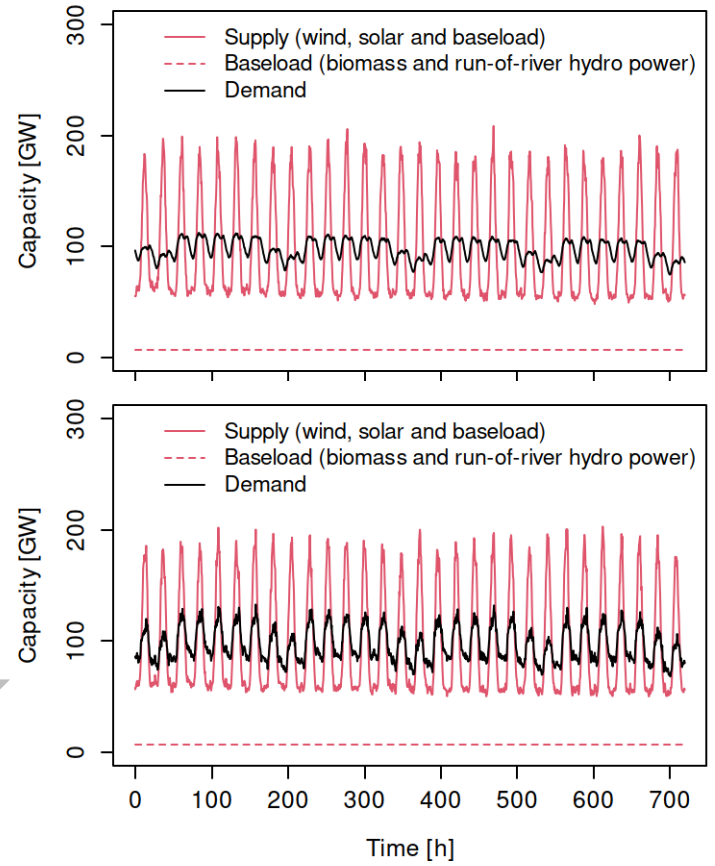
1) Marginal utility: ca. 60 € / MWh, see [15]; full costs > 4000 € / MWh, see [12]
Source: [5], [6], [7], [12], [14], [15], own calculations

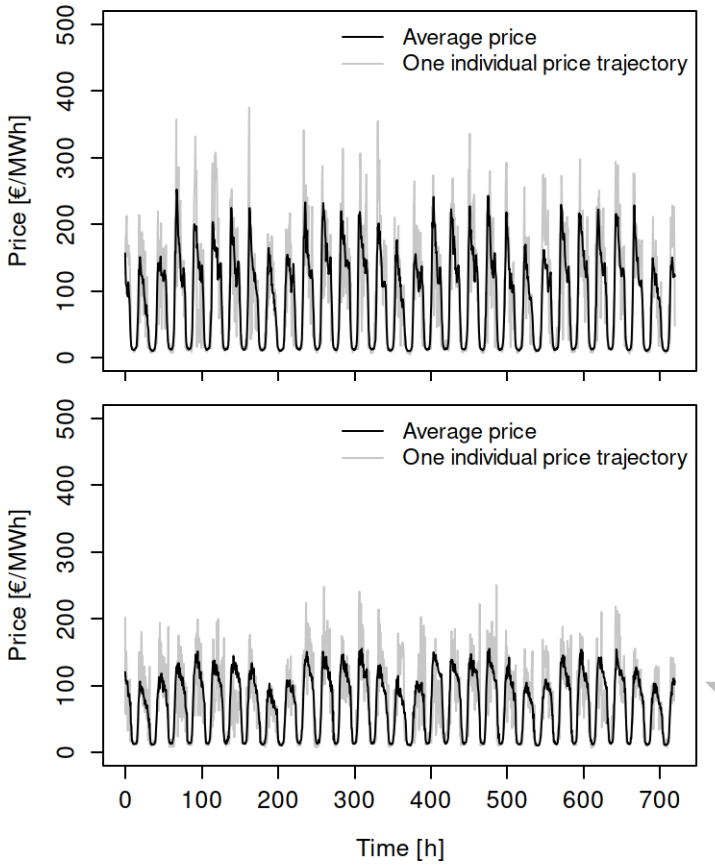
Increasing the demand elasticity reduces both the average price and the volatility

Specific result #2: impact of demand elasticity

Inelastic demand

Elastic demand





Lower price, lower volatility

Source: own calculations

We expect a moderate increase in electricity price and volatility, and an increasing demand elasticity helps keeping the market robust

Key take-aways

- A de-carbonized electricity system combines low-cost renewables with high-cost storage and backup power, thus, the market functions, with higher electricity price and volatility
- Increasing demand elasticity dampens both, the price increase and the volatility increase
- Modelling supply and demand separately, as mean-reverting stochastic processes with time-dependent trends and positive dynamics proves to be effective and efficient

Selected sources particularly for this presentation are as follows, the full bibliography is contained in the article draft

Bibliography (selection)

[1] Barlow: A diffusion model for electricity prices, Mathematical Finance, 2002
[2] Bundesamt für Ausfuhrkontrolle: Erdgasstatistik, 2023
[3] Bundesnetzagentur: Auction results for windpower and solar PV, 2023
[4] Entso-E: several statistics on electricity production and consumption and power generation capacity, 2023
[5] Fraunhofer Institut für Solare Energiesysteme: Wege zu einem klimaneutralen Energiesystem, 2021
[6] Gutachterbericht zur dena-Leitstudie Aufbruch Klimaneutralität, EWI, 2021
[7] Hansen et. al.: Full Energy System Transition […], Renewable and Sustainable Energy Reviews, 2019
[8] Hao et. al.: Seasonal effects on electric vehicle […], Journal of Cleaner Production, 2020
[9] Langrene et. al.: A closed-form Expansion for the Inverse Gamma Model, Econometrics, 2015
[10] Kloeden, Pearson: The numerical solution of stochastic differential equations, JAMS, Series B, 1977
[11] Nelson: ARCH models as diffusion approximations, Journal of Econometrics, 1990
[12] Robinius et. al.: Wege für die Energiewende, FZ Jülich, 2020
[13] Sauer: Computational solution of stochastic differential equations, Wiley: Computational statistics, 2013
[14] Wiese et. al.: Strategies for climate neutrality, Renewable and sustainable energy transition, 2022
[15] Zhang et. al.: Marginal utility of battery energy storage […], Energy Reports, 2022