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On the Long-Term Merit Order Effect of Renewable Energies

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The Merit-Order Effect …

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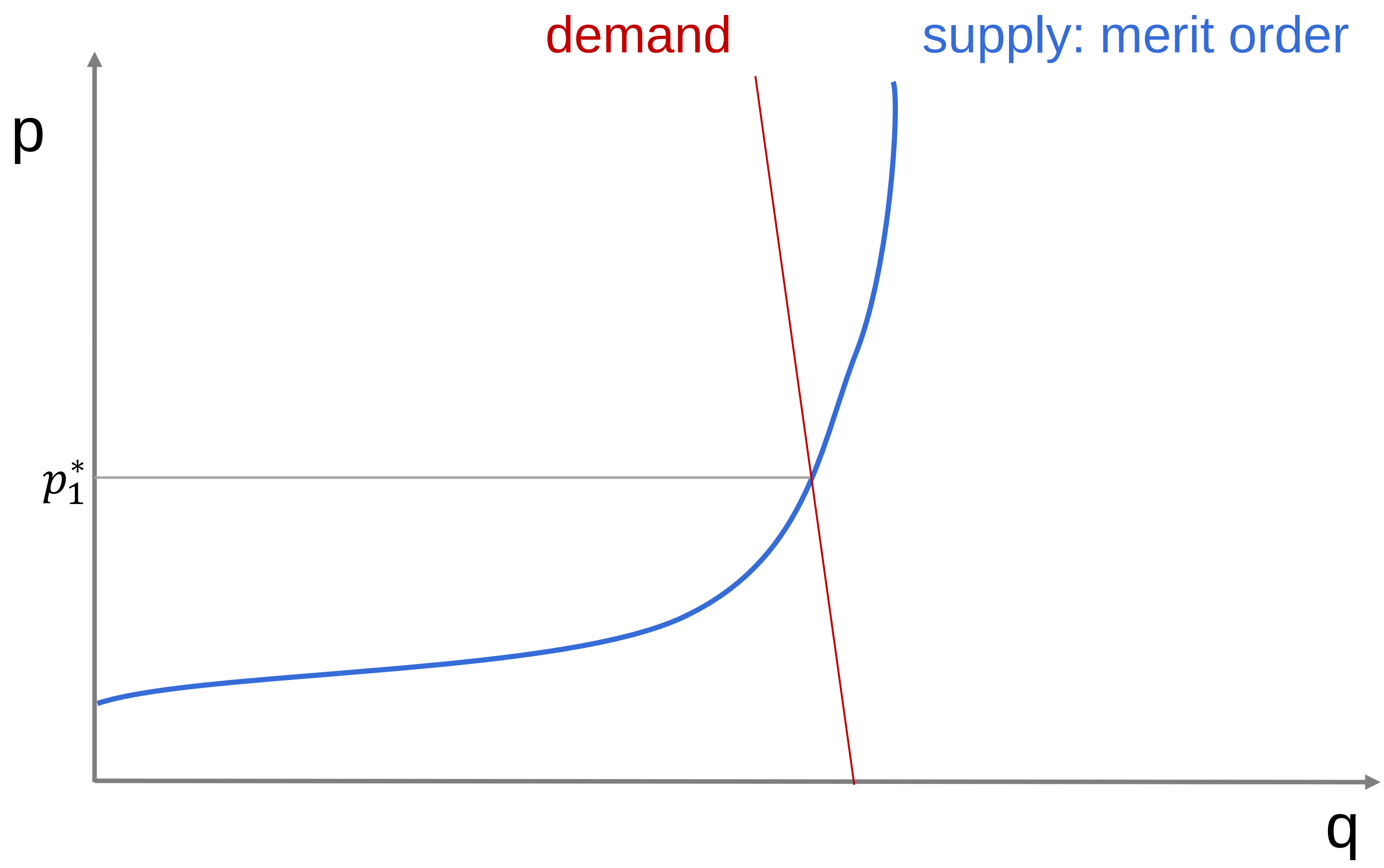
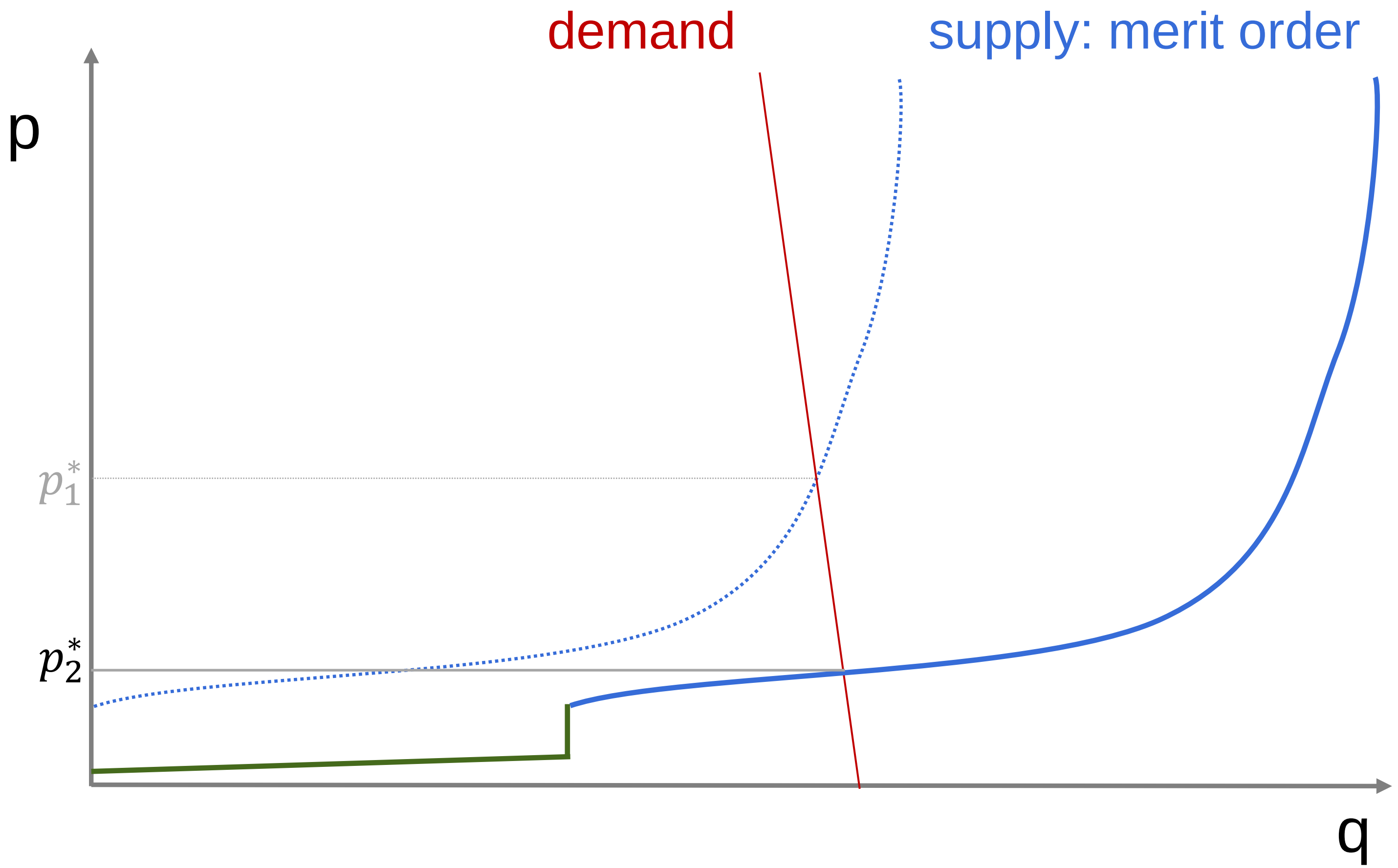
- … measures how wholesale electricity prices are influenced by feed-in from intermittent renewable electricity generators.
- … is interested in average prices over several time periods (e.g. a year)
- ... regards an important policy question (“co-benefit” of renewables for consumers).
- … regards an important business question (prices and price structures are highly relevant for investment decisions on the supply and demand side).

Phase 1: No Renewable Generation



Phase 2: Renewable Generation is Added



Phase 3: Conventional System Adjusts

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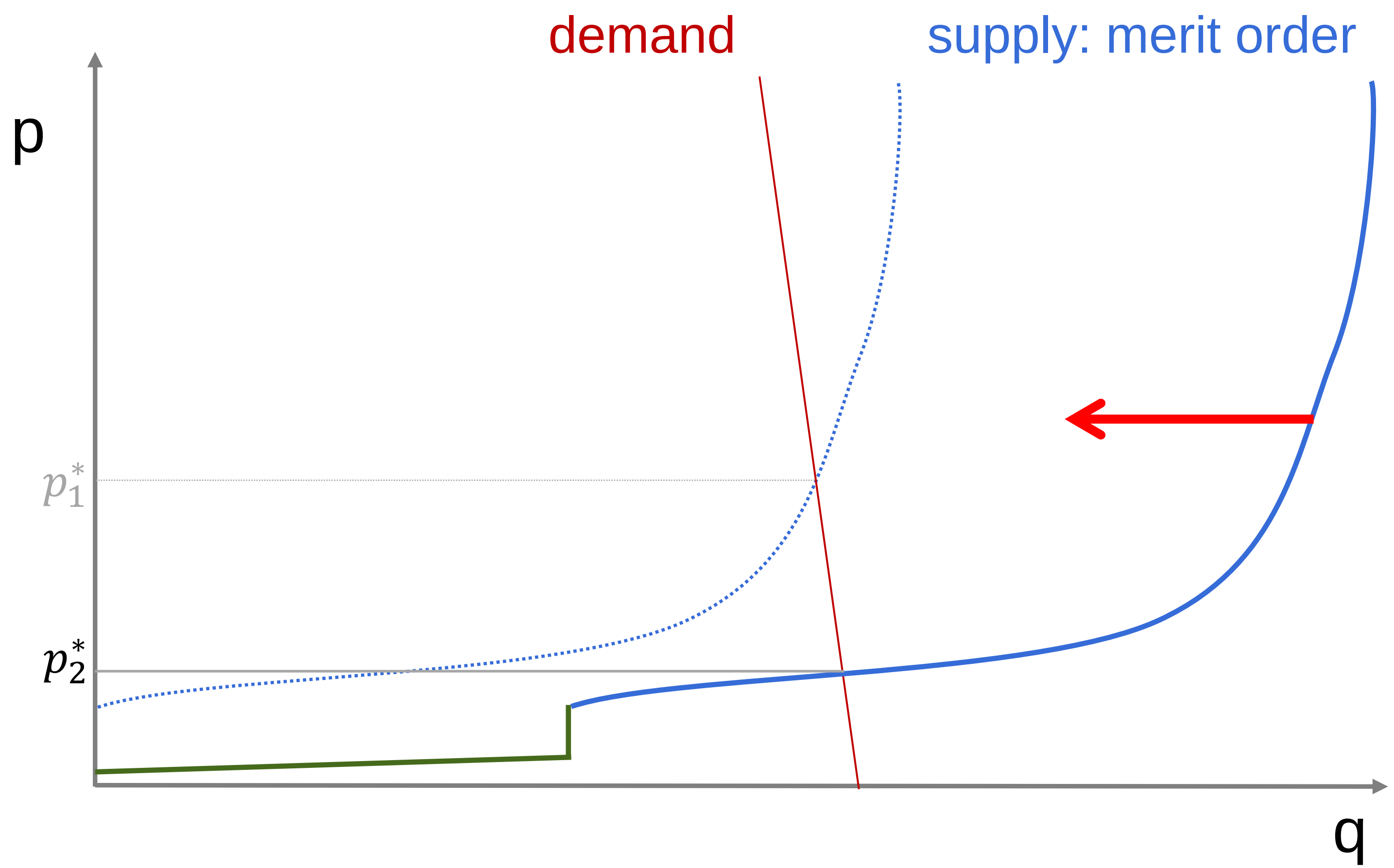
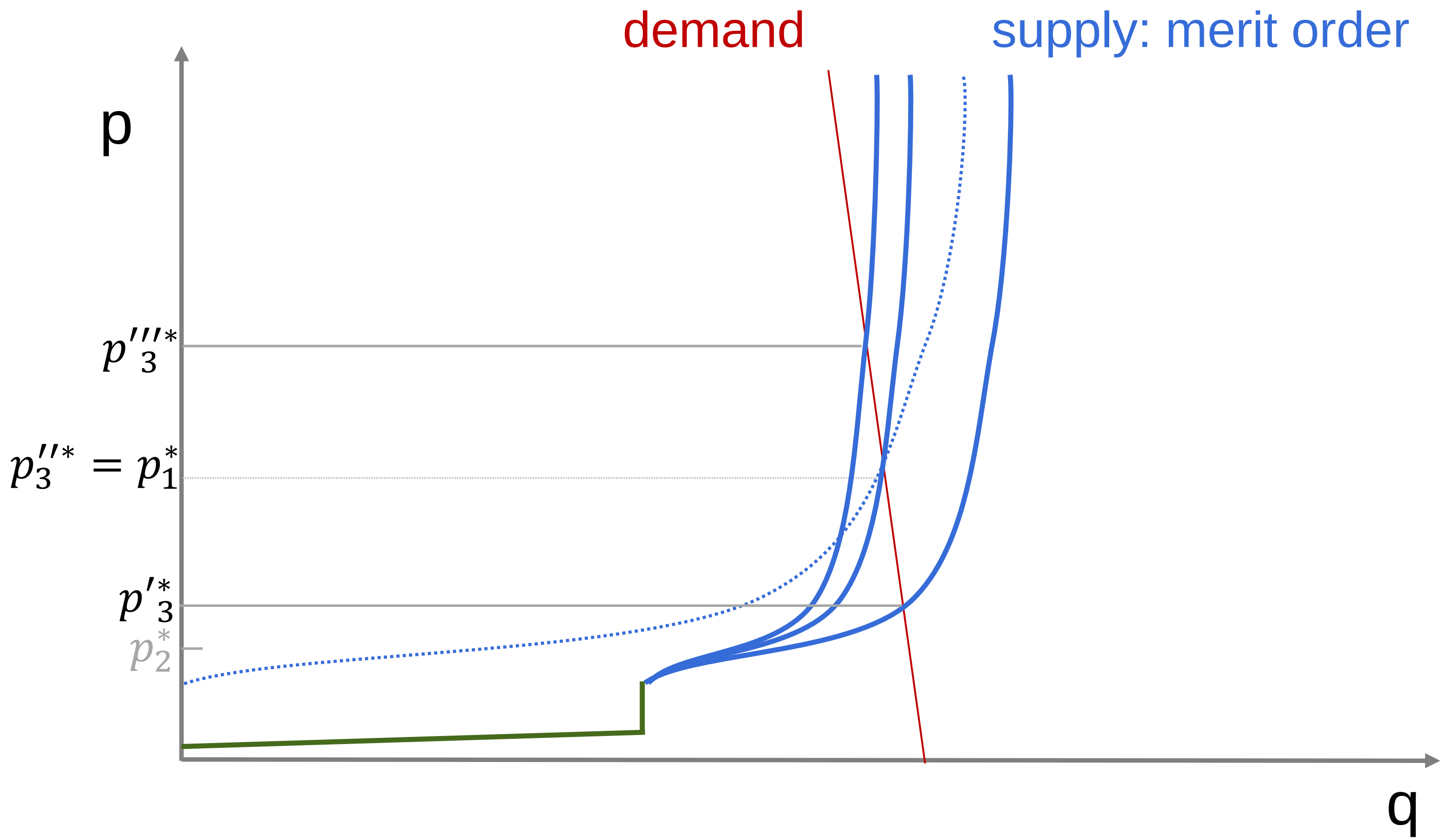


Phase 3: Conventional System Adjusts



Conclusions from the Literature and Contribution

- The merit order effect is quantified in more than 20 scientific papers.
  - Results differ widely (from 10 €/MWh and more to -0.4 €/MWh).
  - Most papers **confirm a short-term merit order effect (**under the assumption that **conventional capacities do not react)**. While constant conventional capacities can be justified in the short term, (at least) one of the two systems compared is **out of equilibrium** and **adjustments will take place**.
  - Papers on these adjustments are
    - extremely rare
    - mostly empirical in nature, focusing on specific markets.
- Our approach is more general because we develop a theoretical model. Our calculation of electricity wholesale market equilibria in investment and dispatch is founded on several theoretical contributions in the peak-load pricing literature. We thus contribute to the literature by presenting clear cut analytical results on the merit order effect, both in the short and in the long term, under varying degrees of competition.

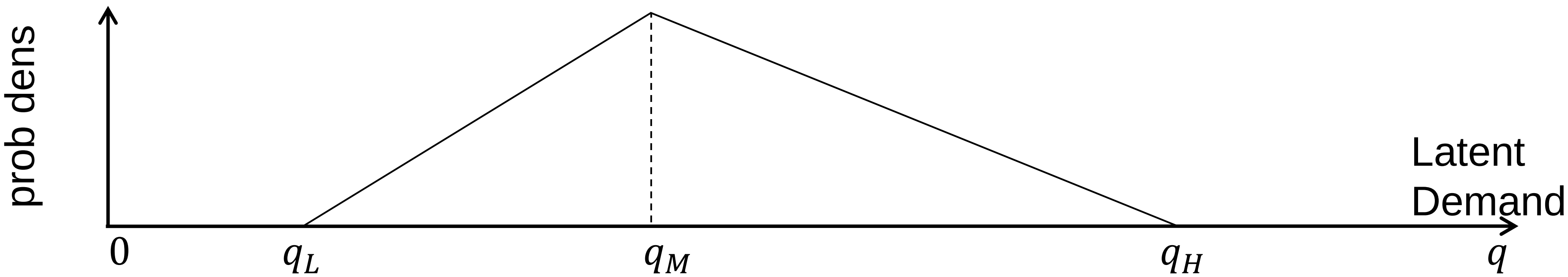
Scenario Comparison

1. Scenario: “baseline” (Scenario 1 could also be seen as the “old world” without electricity generation from intermittent renewable energy sources such as PV and wind.)
   - **Optimal capacity** and **generation** for both **base** and **peak load**
   - **No intermittent generation**.
2. Scenario: “unadjusted system”.
   - **Intermittent renewable** electricity generation capacity **added**
   - **conventional capacities unadjusted** (i.e. equal to scenario 1).
3. Scenario: “adjusted system”. The system adjusts to the presence of renewable energy and investment in **conventional capacity** is **re-optimised**.

Assumptions - Supply

- Two conventional generation technologies, base load (B) and peak load (P).
  - nameplate **capacity** of these generators is given by $\bar{s}_B$ and $\bar{s}_P \in \mathbb{R}^+$.
  - Output (supply): s_B, s_P
    - base load non-rampable and thus constant at $s_B = \bar{s}_B$. By design:
      - addresses the various ramping constraints of thermal capacity
      - enables negative wholesale electricity prices
    - peak load $0 \leq s_P \leq \bar{s}_P$
  - Each generator has marginal cost c_i so that $0 < c_B < c_P$, and fixed cost (per unit of capacity) f_i. To avoid one technology dominating the other, we assume $f_P < f_B$ and $f_B + c_B < f_P + c_P$
  - We assume the wholesale market is the only revenue source for both base load and peak load.

Assumptions - Demand

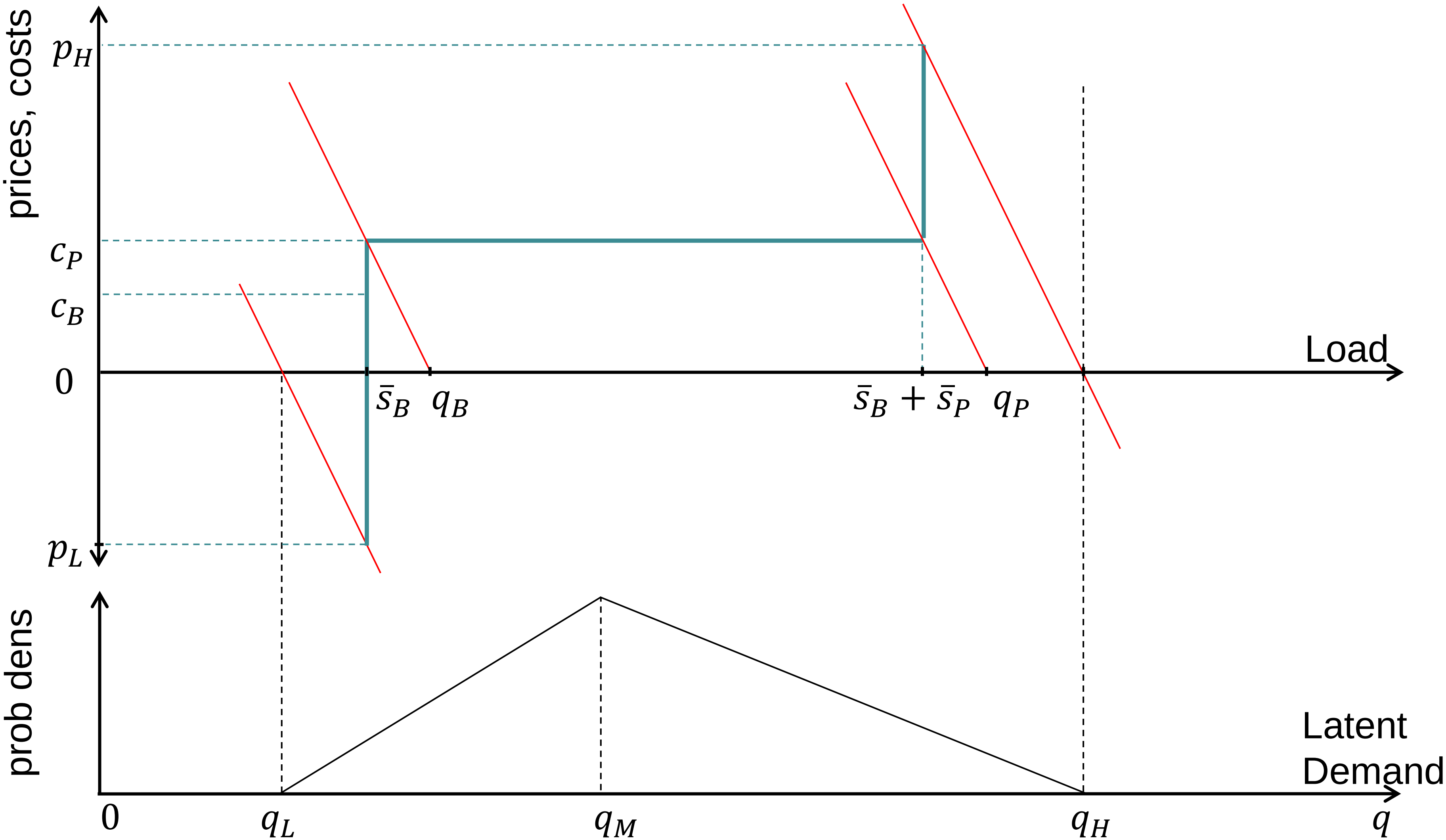


- Triangular probability density function of latent demand
  - latent demand q defined as demand at price zero
  - additional price elasticity added: $v(p) = -p/\theta$, resulting price dependent demand: $q - p/\theta$
- Associated cumulative distribution function:

$$\Phi(q) = \begin{cases} 0 & q \leq q_L \\ (q - q_L)^2/q_{ML} & q_L < q \leq q_M \\ 1 - (q_H - q)^2/q_{HM} & q_M < q < q_H \\ 1 & q \geq q_H \end{cases}$$

with $q_{ML} \equiv (q_H - q_L)(q_M - q_L) \quad \text{and} \quad q_{HM} \equiv (q_H - q_L)(q_H - q_M).$

Scenario 1: Intuition of Equilibrium



Scenario 1: Optimal Aggregated Capacity (Perfect Competition)

- Price spikes (at load levels $q > q_P$) are the only source for peak load profit contributions. Hence, in perfect competition

$$f_P = \int_{q_P}^{q_H} \theta\,(q - q_P)\,\phi(q)\mathrm{d}q$$

- After some calculations, optimal aggregated capacity is:

$$\bar{s} = \bar{s}_B + \bar{s}_P = q_H - c_P/\theta - [3 \cdot f_P \cdot q_{HM}/\theta]^{1/3}$$

- Once aggregated capacity is determined, the share of base load can be derived based on costs equal to revenues:

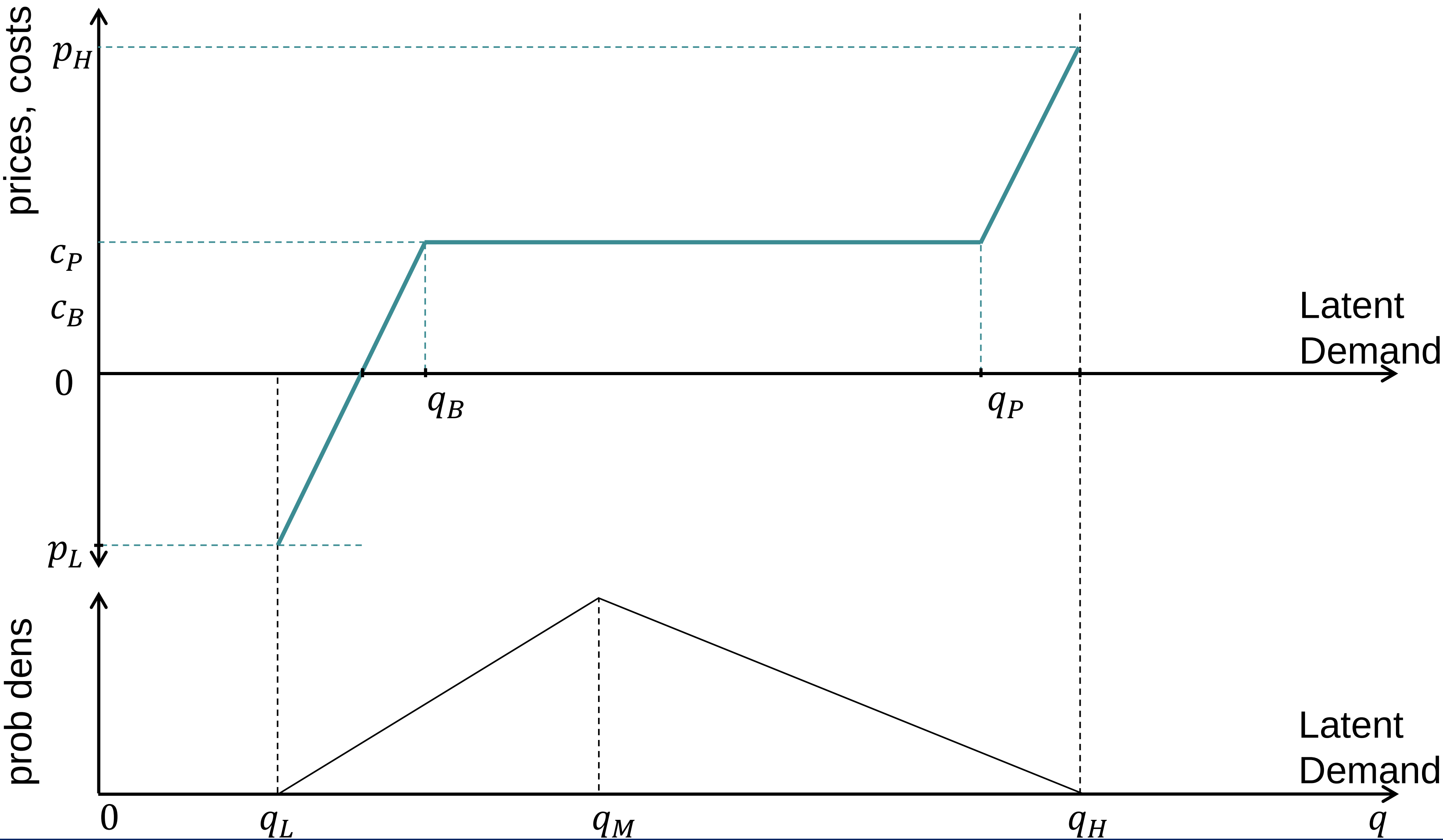
$$f_B + c_B$$

$$= \int_{q_P}^{q_H} \big(c_P + \theta(q - q_P)\big)\phi(q)\mathrm{d}q + \int_{q_B}^{q_P} c_P\phi(q)\mathrm{d}q + \int_{q_L}^{q_B} \big(c_P + \theta(q - q_B)\big)\phi(q)\mathrm{d}q$$

- Finally revealing:

$\bar{s}_B = q_L - c_P/\theta + [3\Delta q_{ML}/\theta]^{1/3}$, where $\Delta \equiv (c_P + f_P) - (f_B + c_B)$

Equilibrium Price Structure



Average Price in Scenario 1 under Perfect Competition

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- Define $\bar{p} = \int_{q_L}^{q_H} p(q)\phi(q)\mathrm{d}q$
- Based on the information derived so far, this can be split in three segments: $\bar{p} = \int_{q_P}^{q_H}\big(c_P + \theta(q - q_P)\big)\phi(q)\mathrm{d}q + \int_{q_B}^{q_P} c_P\phi(q)\mathrm{d}q + \int_{q_L}^{q_B}\big(c_P + \theta(q - q_B)\big)\phi(q)\mathrm{d}q$
- However, we have already seen this expression before. Hence, we can calculate:

$$\bar{p} = \int_{q_P}^{q_H}\big(c_P + \theta(q - q_P)\big)\phi(q)\mathrm{d}q + \int_{q_B}^{q_P} c_P\phi(q)\mathrm{d}q + \int_{q_L}^{q_B}\big(c_P + \theta(q - q_B)\big)\phi(q)\mathrm{d}q$$
$$= f_B + c_B$$

- **Key result**:
  The average price in scenario 1 assuming perfect competition is $\bar{p} = f_B + c_B$

Scenario 1 - Monopolistic Base Load

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- Markets for electricity generation are rarely perfectly competitive, oligopoly and monopoly issues are often present.
- We analyse the case of a monopolistic base load operator (motivated by large and capital intensive base load) to analyse imperfect competition.
- Under this assumption, we find (using subscript m for monopoly):
  - $f_B + c_B = \bar{p}(\bar{s}_{B,m}) + \bar{p}'(\bar{s}_{B,m})\bar{s}_{B,m} = c_P + f_P - \theta\Phi(q_{B,m})\left[\frac{q_{B,m}-q_L}{3} + \bar{s}_{B,m}\right]$

    which yields $\bar{s}_{B,m} = \frac{3}{4}(q_L - c_P/\theta) + \frac{1}{4G}(q_L - c_P/\theta)^2 + \frac{G}{4}$

    (where $G \equiv \left(24q_{ML}\Delta/\theta + 4\sqrt{4(3q_{ML}\Delta/\theta)^2 - (3q_{ML}\Delta/\theta)(q_L - c_P/\theta)^3} - (q_L - c_P/\theta)^3\right)^{1/3}$)
  - $\boldsymbol{\bar{p}_m = f_B + c_B + \underbrace{\bar{s}_{B,m} \cdot \theta \cdot \Phi(\bar{s}_{B,m} + c_P/\theta)}_{> 0}}$
- **Key result**:
  The average price in scenario 1 assuming monopolistic base load increases by $\bar{s}_{B,m} \cdot \theta \cdot \Phi(\bar{s}_{B,m} + c_P/\theta)$

Scenario 2: RES Enter the Scene

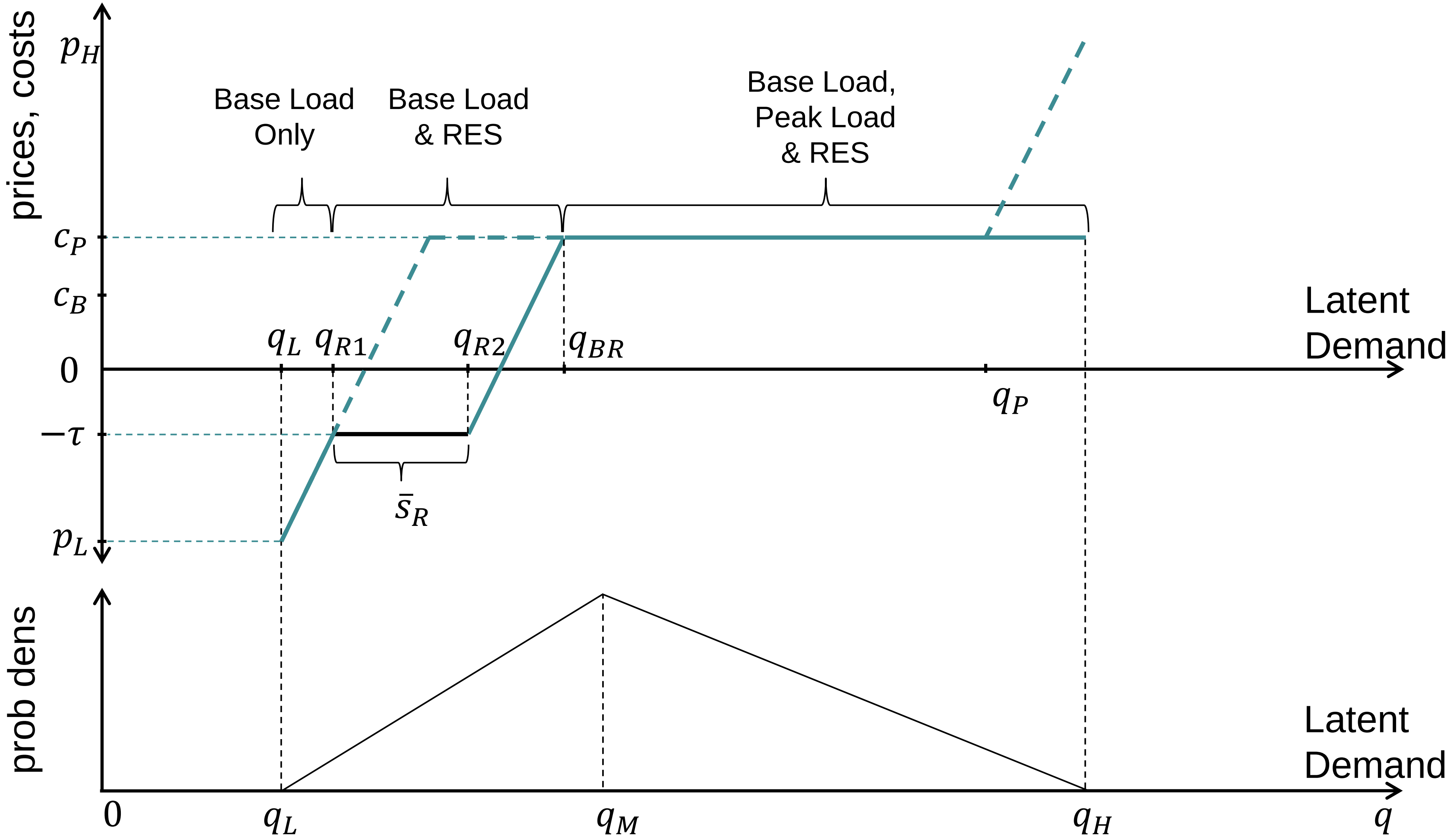
- Additional assumptions for renewable energy sources (RES)
  - RES capacity is determined exogenously, e.g. resulting from policy targets, achieved with a production subsidy τ
  - Capacity is $\bar{s}_R$, output is s_R, fixed costs are f_R and variable costs are $c_R = 0$.
  - RES are (un)available with the following probability density function:

$$Z(a) = \begin{cases} 1-\alpha & a=0 \\ \alpha & a=1 \end{cases}$$

  - RES can be curtailed (when prices would otherwise drop below $-\tau$). RES generation s_R is thus $0 \leq s_R \leq a\bar{s}_R$.
  - In scenario 2, $\bar{s}_B$ and $\bar{s}_P$ remain unchanged (by assumption, “short term merit order effect”)
  - $\bar{s}_R \geq q_H - q_P$, i.e. no price spike when RES available.
- Three states for the intermittent generator with respect to its output, depending on availability, latent demand and installed base load capacity result:

$$s_R = \begin{cases} 0 & if\ either\ a=0\ or\ a=1 \wedge q \leq \bar{s}_B - \tau/\theta \equiv q_{R1} \\ q - q_{R1} & if\ a=1 \wedge q_{R1} < q < q_{R2} \\ \bar{s}_R & if\ a=1 \wedge q \geq \bar{s}_B + \bar{s}_R - \tau/\theta \equiv q_{R2} \end{cases}$$

Resulting Price Structure (Illustration)



Results Scenario 2 - Perfect Competition

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- **Capacities**: Unchanged (by assumption)
- **Average price** can be expressed depending on RES availability:

$$\bar{p}_c^{\square} = (1-\alpha)\bar{p}_{c,n}^{\square} + \alpha\bar{p}_{c,a}^{\square}$$

(where superscript $^{\square}$ is used for scenario 2, subscript $_c$ for the competitive case and subscripts $_a$ and $_n$ denote RES availability)

  - when RES are unavailable, same price as scenario 1:

$$\bar{p}_{c,n}^{\square} = \bar{p}_c^{\circ} = f_B + c_B$$

  - when RES are available, $\bar{p}_{c,a}^{\square} < \bar{p}_c^{\circ}$
- **Key Result**: Under perfect competition, the short term merit order effect is unambiguously reducing the average wholesale market price for electricity.

Results Scenario 2 - Natural Monopoly

- Capacities: Unchanged (by assumption)
- Average price depends on RES availability:

$$\bar{p}_m^{\square} = (1-\alpha)\bar{p}_{m,n}^{\square} + \alpha\bar{p}_{m,a}^{\square}$$

  - when RES are unavailable, same price as scenario 1:

$$\bar{p}_{m,n}^{\square} = f_B + c_B + \bar{s}_{B,m} \cdot \theta \cdot \Phi\left(\bar{s}_{B,m} + c_P/\theta\right)$$

  - when RES are available,

$$\bar{p}_{m,a}^{\square} < \bar{p}_m^{\circ}$$

- Same reasoning as in competitive case reveals $\bar{p}_m^{\square} < \bar{p}_m^{\circ}$, i.e.
  Key result: the short term merit order effect can be confirmed for monopolistic supply of base load.

Scenario 3 - Assumptions

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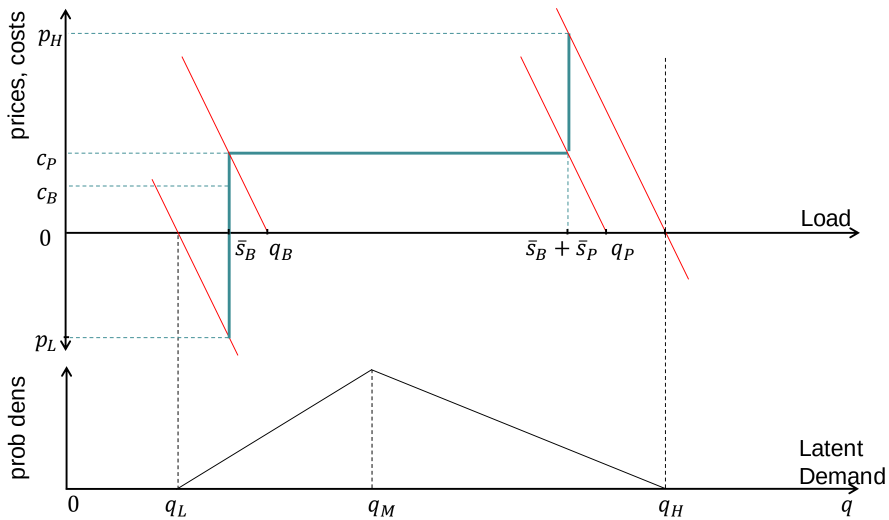
- $\bar{s}^{\bullet} \equiv \bar{s}_B^{\bullet} + \bar{s}_P^{\bullet}$, where the $^{\bullet}$-superscript denotes the long term scenario, furthermore: $q_P^{\bullet} = \bar{s}^{\bullet} + c_P/\theta$
- RES capacity $\bar{s}_R^{\bullet}$ in the long term is exogenously given
- s_R, when available, eliminates price spikes: $q_H - q_P \leq \bar{s}_R$. Consequence: spikes must be higher/longer as they appear with reduced probability $(1-\alpha)$



Scenario 3 - Results under perfect Competition

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- Zero profit condition for peak load requires: $f_P = (1-\alpha)\int_{q_P}^{q_H} \theta\,(q-q_P)\,\phi(q)\mathrm{d}q$
- Solving this equation for $\bar{s}_c^{\bullet}$ (contained in $q_{P,c}^{\bullet}$) yields

$$\bar{s}_c^{\bullet} = q_H - c_P/\theta - \left[\frac{3\cdot f_P \cdot q_{HM}}{\theta(1-\alpha)}\right]^{1/3}$$

- Only difference to scenario 1: $(1-\alpha)$. Consequence: Less (aggregated) conventional capacity.
- The share of base load capacity will adjust based on base load's zero profit condition $\frac{\Delta}{\theta} = \psi(q_{B,c}) + \alpha\left[\psi(q_{B,c}) - \psi(q_{BR,c}) + \psi(q_{R2,c}) - \psi(q_{R1,c})\right]$ with $\psi(q_x) \equiv \max(0, q_x - q_L)^3/3q_{ML}$
- While this expression is non-linear, we can compare it to scenario 1:
  Key Result: In the long term, the combined peak load and base load capacity will be lower than in the case without renewables ($\bar{s}_c^{\bullet} < \bar{s}_c^{\circ}$). The base load capacity will decrease in response to adding renewables ($\mathrm{d}\bar{s}_{B,c}^{\bullet}/\mathrm{d}\bar{s}_R^{\bullet} < 0$). The net effect on peak load supply is ambiguous.
- **Key Result**: Average price is still driven by base load's zero profit condition: $\bar{p}_c^{\bullet} = f_B + c_B$. Under the given assumptions, we prove that the long term merit order effect is zero.

Scenario 3 - Results for monopolistic base load

- Again, base load is assumed to be provided monopolistically while peak load is competitive. The latter assumption, regardless of the amount of base load, implies that optimal aggregated capacity in this case is the same as under perfect competition, as only the cost structure of peak load determines aggregated capacity!
- Hence, the monopolist determines the share of base to peak.
- Furthermore, we show in the paper that
  - the monopolistic price after the addition of RES (scenario 3) is below the baseline price (scenario 1), i.e. $\bar{p}_m^{\bullet} < \bar{p}_m^{\circ}$ and
  - the amount of base load capacity also declines, i.e. $\bar{s}_{B,m}^{\bullet} < \bar{s}_{B,m}^{\circ}$.
- **Key Result**: With monopolistic base load generation, the average price even after adjustment of conventional capacity (scenario 3) is below the baseline (scenario 1). The intuition is that RES production reduces the monopolistic supplier's incentive to increase prices via capacity withholding.

Conclusion

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- We show that the majority of the merit order effect is transitory.
- The situation changes when moving away from perfect competition. We proved in this paper that there is a strictly negative long term merit order effect in a monopolistic setting.
- Furthermore, our stylised model allows (and will indeed generate with many parameterisations) negative prices.
- Our results are vital for market designers and policy makers because we answer major questions regarding the structural changes caused by intermittent RES capacity additions.
- The model developed in our paper is versatile because the methodological core captures supply and demand stochasticity in an analytically tractable way.

Thank you for your attention!

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