Norwegian University of Science and Technology

Profitability of power generation and energy storage in low-carbon electricity markets:
A fundamental analysis

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Common hypohesis:

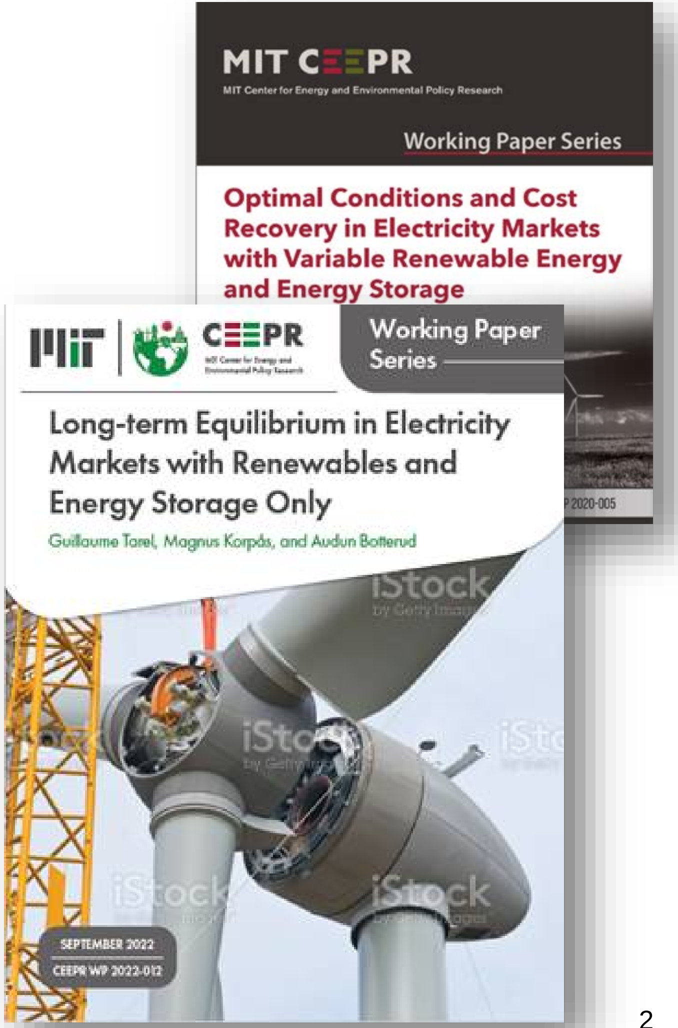
- Traditional electricity markets fail under large-scale penetration of wind and solar
  - Wind and solar have zero marginal cost
- Prices collapse and costs are not recovered in the long run

Our first result:

- All plants recover their costs in (perfect) energy-only markets with wind and solar
  - Holds true in general without energy storage
  - Holds true under certain simplifications with energy storage
- Think twice before embarking on complete re-design of electricity markets

Next step:

- Solve the equilibrium problem for a system without thermal generation



Investments in VRE and Storage

- Investments in VRE and energy storage have been driven, in part, by incentive schemes and policies
  - Feed-in tariffs/premiums, auction schemes, carbon pricing, net metering (Europe)
  - Production and investment tax credits, renewable portfolio standards, net metering, energy storage mandates (United States)
- Rapid reduction in costs for VRE and Storage
- How do these technologies influence thermal generation investments and market equilibrium in a competitive market?
  - Schmalensee, MIT (2019)
  - Joskow, MIT (2019)

System Optimality and Market Equilibrium

- Most electricity markets are based on marginal cost pricing
- Gives the optimal solution for the system in theory
  - System demand is met at minimum costs
  - All GenCos (price-takers) maximize their profits and recover their costs (Green 2000, Stoft 2002)

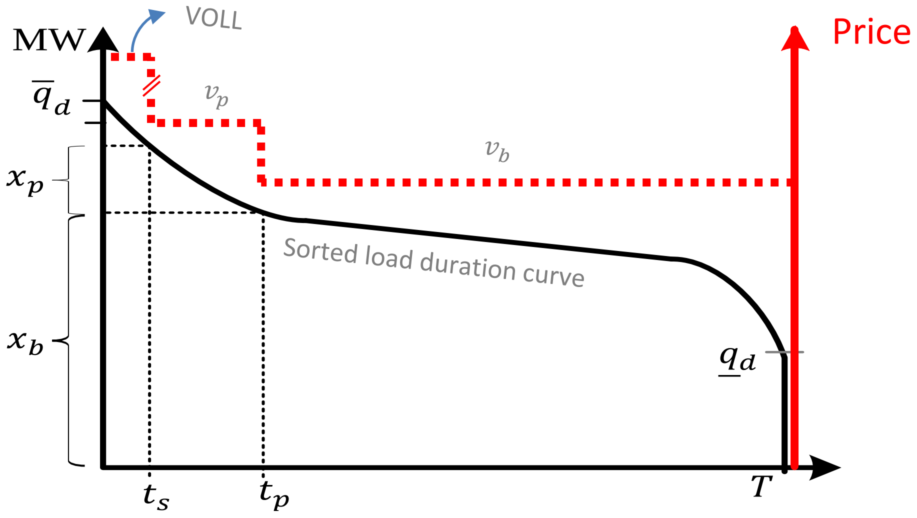
- We assume energy-only markets
  - Scarcity pricing ensure cost recovery of peaker (and all other) plants
  - No explicity capacity remuneration mechansism considered
    - They do influence market outcomes and prices (Kwon et al. 2019)
  - No direct incentive schemes for VRE and EES
    - Competing on equal terms as other technologies

Justification for marginal pricing

- Minimization of fixed (F_i) and variable (v_j) costs

$$\min_{x_i, q_k(t), q_{e-}(t)} C = \sum_i F_i x_i + \sum_j v_j \int_0^T q_j(t)\, dt$$

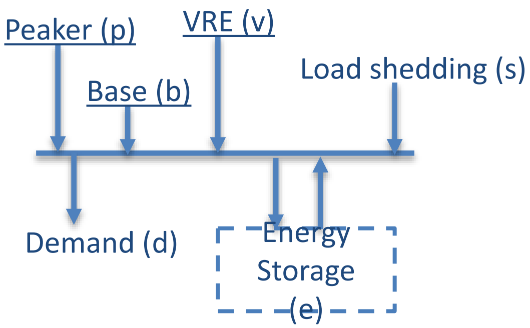
- One can show that at optimality for the system
  - Energy must be priced at the marginal cost
  - Except during shedding: then it must be VOLL
  - All individual generators are able to recover their cost (« zero » profit)
- Valid under perfect market conditions, including no barriers to exit and entry



M. Korpås, A. Botterud. *Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage*, MIT CEEPR Working Paper 2020-005, March 2020.

Keeping fossil generators, adding renewables

- By using the <u>same formalism</u>, one can show that an optimal solution still exists, with pricing at the marginal cost **under certain conditions**
  - Fossil generators (with a marginal cost) are still present
  - RES can be curtailed
  - RES have to recover all its fixed costs through the market (no subsidies)
  - Simplified energy storage representation



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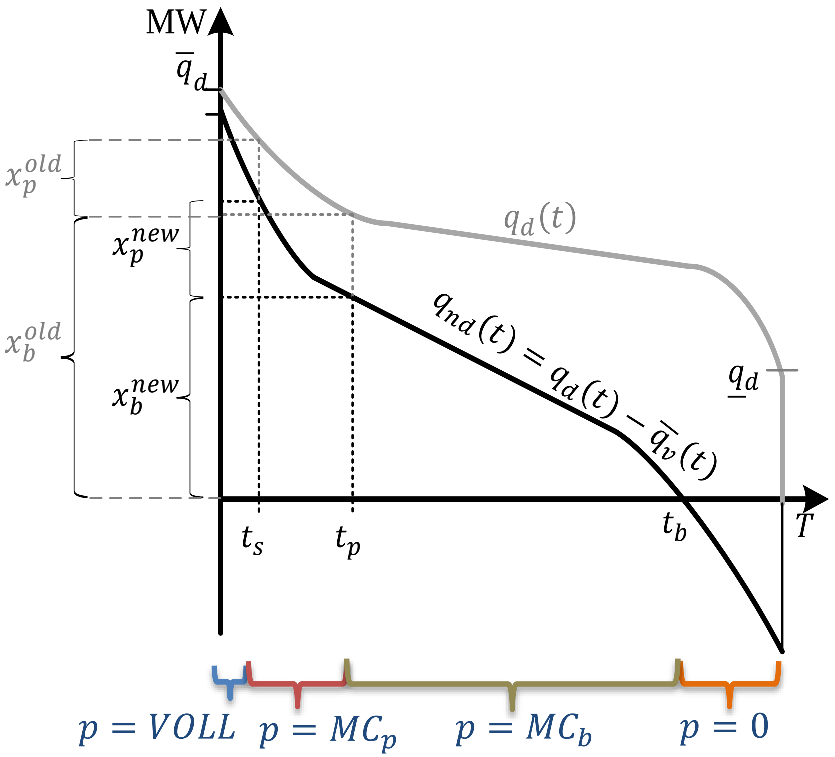
Korpås M., Tarel G., Holttinen H., Botterud A. *Profitability of Power Plants and Energy Storage in Low-Carbon Electricity Markets: A Fundamental Analysis*. Chaire European electricity markets, Manuscript, June 2020.

Market Equilibrium with VRE



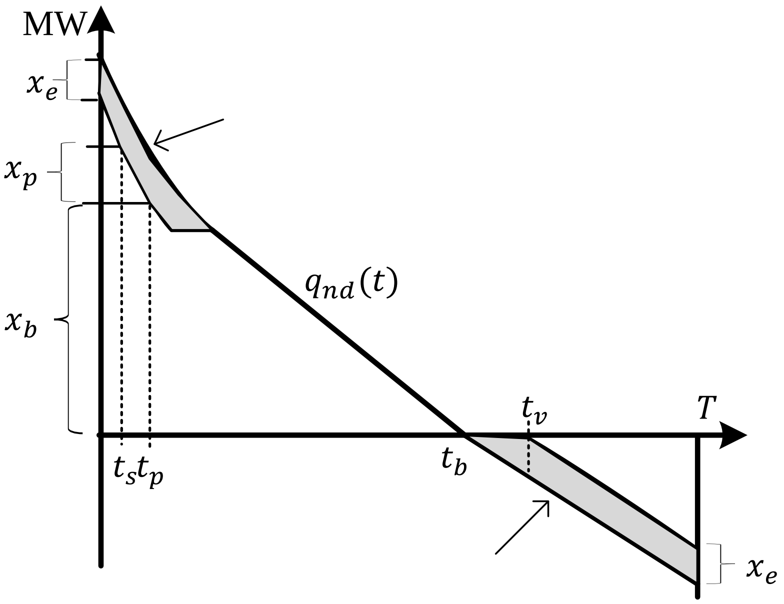
- Net demand = Demand – VRE output
- Cheap VRE will give negative Net demand
- Optimal t_s and t_p are independent of VRE level (Cost recovery)
- Base duration t_b is determined from the VRE optimality condition
- VRE is the marginal generator for $t > t_b$
  - Price p = 0
- Introduction of (competitive) VRE tends to give
  - Less baseplant capacity and energy
  - Slightly more peaker capacity
  - Slightly more load shedding
  - Some VRE curtailment

Market equilibrium with EES

- EES is challenging to include in duration curve modelling due to the storage level constraint
- We can model power capacity x_e and round-trip efficiency η_e explicitly, but not kWh constraint

- We have derived optimality conditions for different (simplified) EES operating assumptions

EES for surplus VRE. «Unlimited storage»



- Optimality condition for EES determines the duration of maximum charging
  - $t \leq t_b$: Price set by most expensive generator in operation.
  - $t_b < t < t_v$: Price set by the storage opportunity cost. It is the value of one more kWh stored energy. $p = \eta_e \cdot VC_b$
  - $t \geq t_v$: Price set by VRE. $p = v_v = 0$
- Introduction of EES creates a new price segment where EES is the marginal load
  - This increases the optimal amount of VRE in the market
  - Thermal is reduced further

What happens with 0 thermal generators?

(Assuming only MW-constraints on storage)

$$\min_{x_e, x_v, q_k(t)} C = F_e x_e + F_v x_v + v_s \int_0^T q_s(t)\, dt, \;\; k \in \{s, v, e, e-\}$$

$$\text{s.t.} \quad q_d(t) - q_v(t) - q_e(t) + q_{e-}(t) - q_s(t) = 0$$

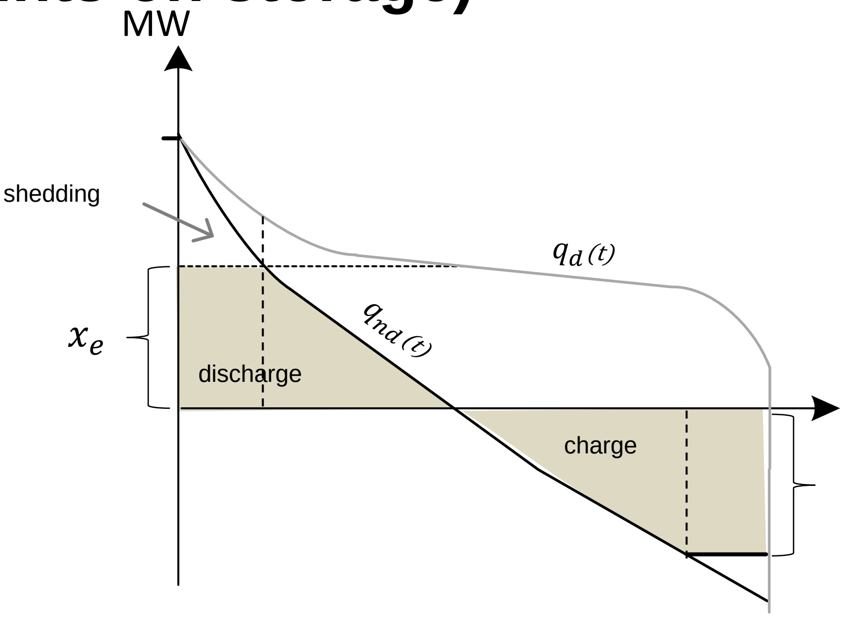
$$-q_k(t) \leq 0 \;,\;\; k \in \{s, v, e, e-\}$$

$$q_e(t) - x_e \leq 0 \,, \qquad q_{e-}(t) - x_e \leq 0$$

$$q_v(t) - AF_v(t) x_v \leq 0$$

$$\frac{dE_e(t)}{dt} = \eta_e \cdot q_{e-}(t) - \frac{q_{e+}(t)}{\eta_{e+}}$$

$$\eta_e \int_0^T q_{e-}(t)dt - \int_0^T q_e(t)dt = 0$$



If energy is priced using variable costs, it will be 0 all the time except during shedding (VOLL)

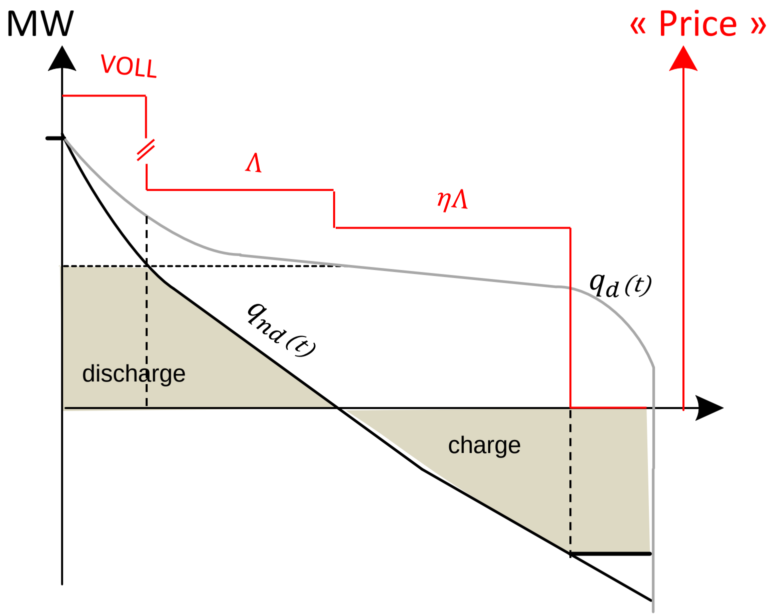
Result

- A mathematically acceptable solution (confirmed using a numerical model) is an equilibrium based on the following « prices » during charge and discharge periods

$$\frac{F_v}{t_e AF_v^{[0,t_e]} + \eta_e (t_v - t_e) AF_v^{[t_v,t_e]}} = \Lambda = \frac{F_e}{\eta_e (T - t_v)}$$

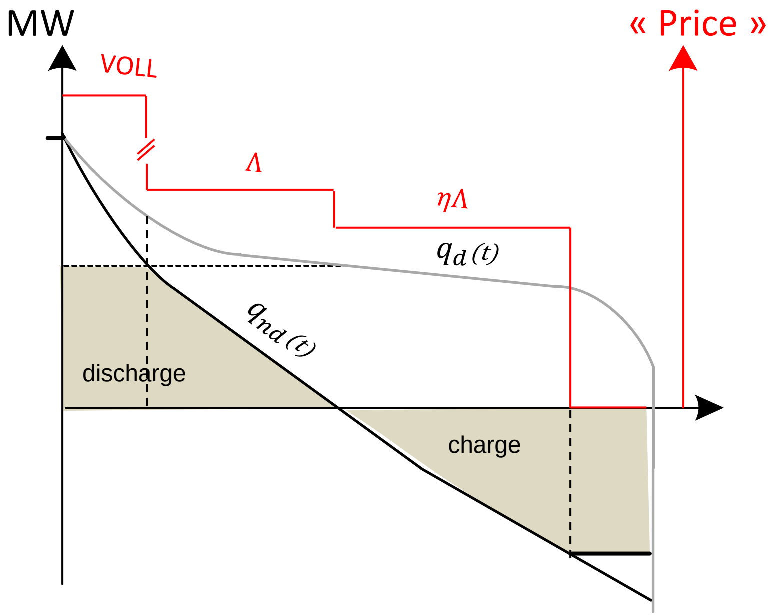
VRE condition Storage condition

- time-dependent « prices » that depend on fixed costs



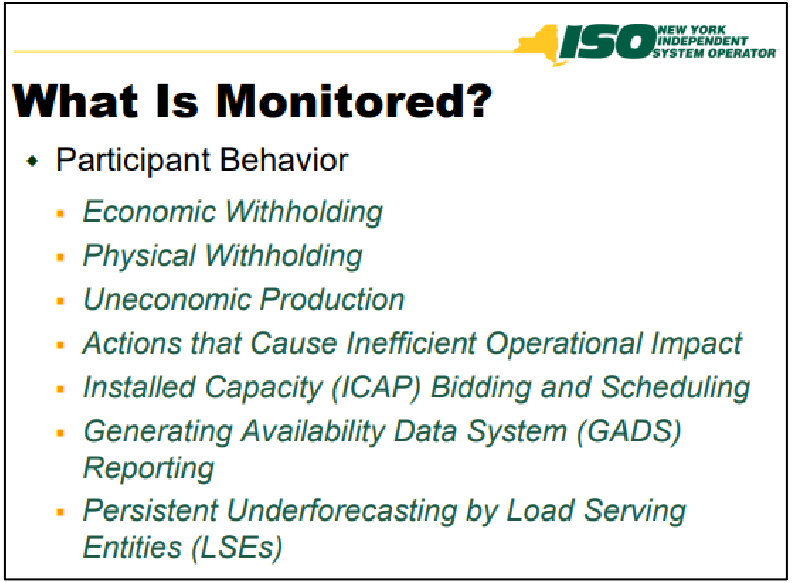
Result

- Valid in a case with storage expensive compared to wind generation (in $/MW)
- There exists an equilibrium (cost recovery, minimized to cost) when using those « prices »



Does it make more than mathematical sense ?

- Energy-only market with no variable costs: generators could compete to offer the lowest possible prices →collapse of prices to 0 throughout the year
- Generators could be supervised to offer their energy at prices > 0
- The supervision of prices offered by generators already exists. For example, market monitoring is used by NY-ISO (“Power Mitigation Measures”)
  - Economic withholding (*“submitting Bids for an Electric Facility that are unjustifiably high”)*
  - The very existence of power mitigation measures is an interesting element



NY-ISO. (2012). Market Monitoring & Market Power Mitigation. https://www.nyiso.com/documents/20142/1392242/Market_Monitoring_and_Market_Power_Mitigation_-_Belinda_Thornton_-_01-19-12.pdf/dcd6fa5c-79c3-d247-1a3c-602f48d96a83

Conclusions

- For a system with variable costs, ideal energy-only markets create prices that recovers all fixed costs
  - Holds for MW-constrained storage
  - Not solved (yet) for storage with MW and MWh constraints
- Next, we have shown a theoretical analysis for an energy-only market **with no variable costs**
- Results indicate that VRE generators and storage could recover their costs as long as:
  - They offer their energy hourly using « prices » dependent on their fixed costs
  - They are supervised for doing so