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Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage

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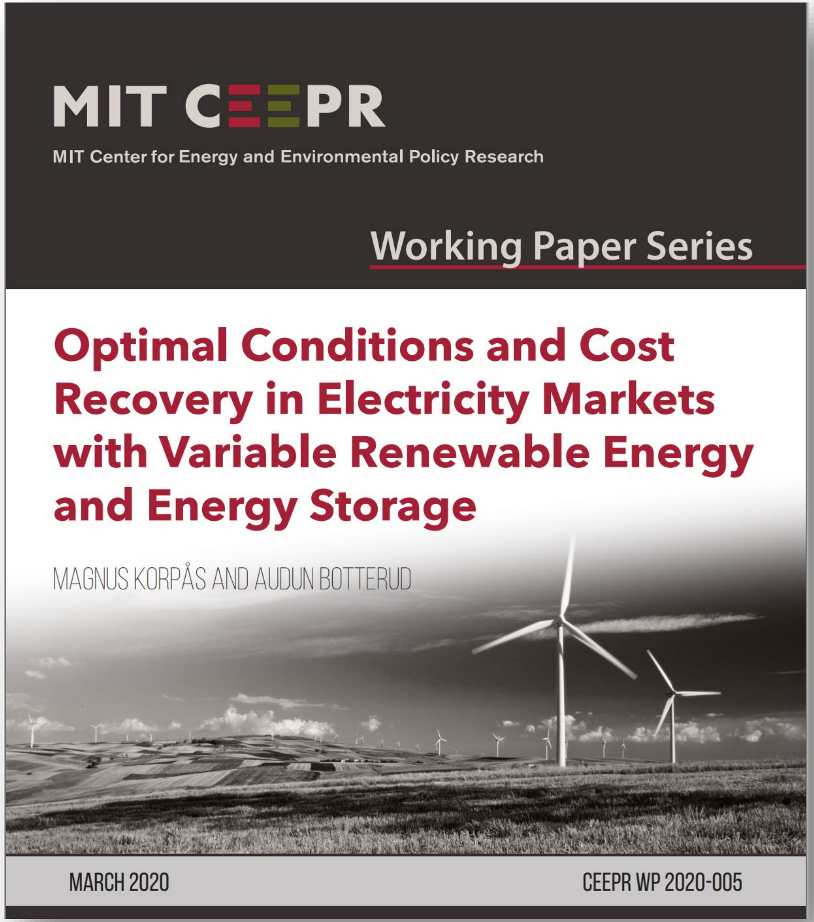
Common hypothesis:

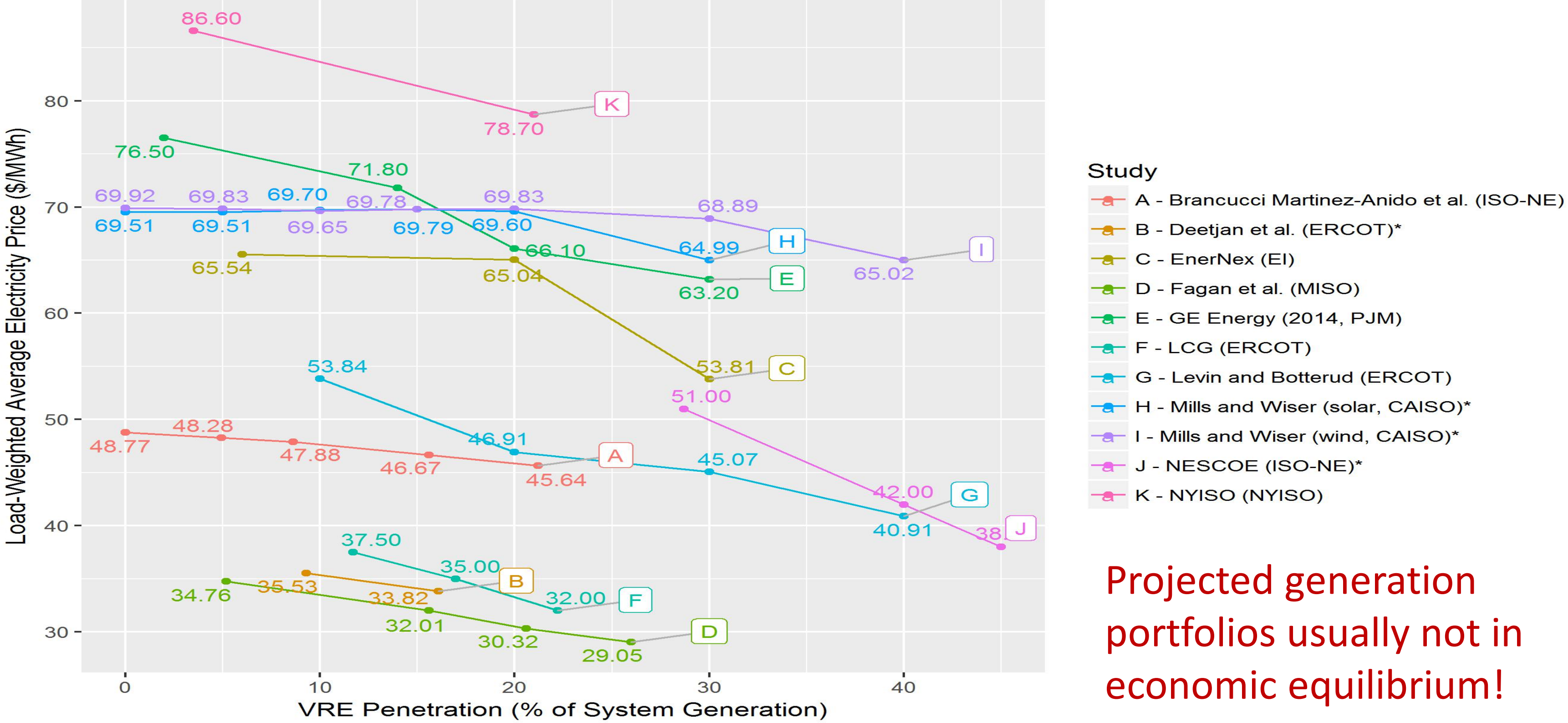
- Traditional electricity markets fail under large-scale penetration of wind and solar
    - Wind and solar have zero marginal cost
- Prices collapse and costs are not recovered in the long run

Our main result:

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



Prediction of Future Price Impacts of VRE



Projected generation portfolios usually not in economic equilibrium!

Mills et al. , 2020

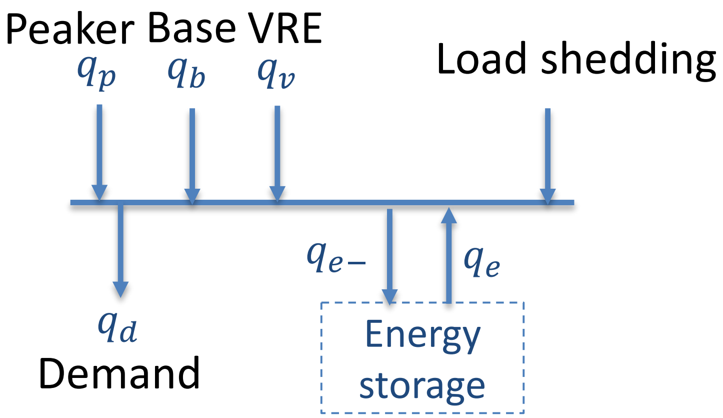
Investments in Variable Renewables and Storage

- Investments in variable renewable energy (VRE) and energy storage (ES) have been driven, in part, by incentive schemes
  - 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 ES
- 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 explicit capacity remuneration mechanism considered
    - They do influence market outcomes and prices (Kwon et al. 2019)
  - No direct incentive schemes for VRE and ES
    - Competing on equal terms with other technologies

System Cost Minimization Problem



$$\min_{x_i} C = \sum_i F_i x_i + \sum_j v_j \int_0^T q_j(t)\,dt$$ Total cost

$$\text{s.t.} \quad q_d(t) - \sum_k q_k(t) + q_{e-}(t) = 0$$ Load balance

$$-q_k(t) \le 0 \,, \qquad -q_{e-}(t) \le 0$$

$$q_l(t) - x_l \le 0 \,, \qquad q_{e-}(t) - x_e \le 0$$

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

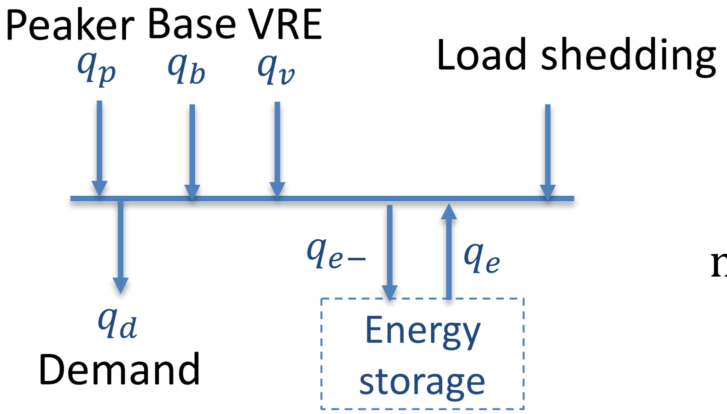
Capacity constraints

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

Sets: $i \in \{p, b, v, e\}$, $j \in \{s, p, b\}$, $k \in \{s, p, b, v, e\}$, $l \in \{p, b, e\}$

Generation and demand: q
Capacity: x
Fixed cost: F
Variable cost: v
Availability factor: AF

Profit Maximization for Technology *i*



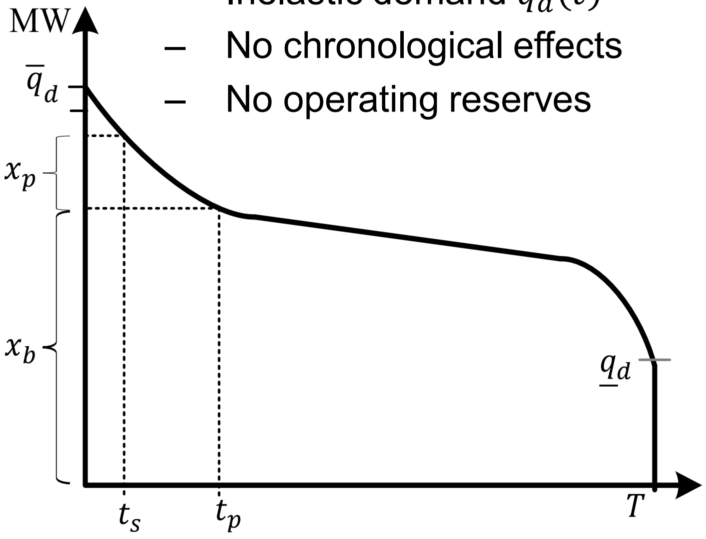
$$\max \pi_i = AR_i - AC_i = \int_0^T (p(t) - v_i) q_i(t) dt - F_i x_i$$

Generation and demand: q
Capacity: x
Fixed cost: F
Variable cost: v

Electricity price: p
Annual Revenue: AR
Annual Cost: AC

Market Equilibrium with Thermal Generation

- Load duration curve approach
  - Green (2000), Stoft (2002)
  - Inelastic demand $q_d(t)$
  - No chronological effects
  - No operating reserves



t_s- duration of load shedding

t_p- duration of peaker operation

- System optimality conditions gives optimal durations of all generators i

$$\min C \Rightarrow \frac{\partial C}{\partial x_i} = 0$$

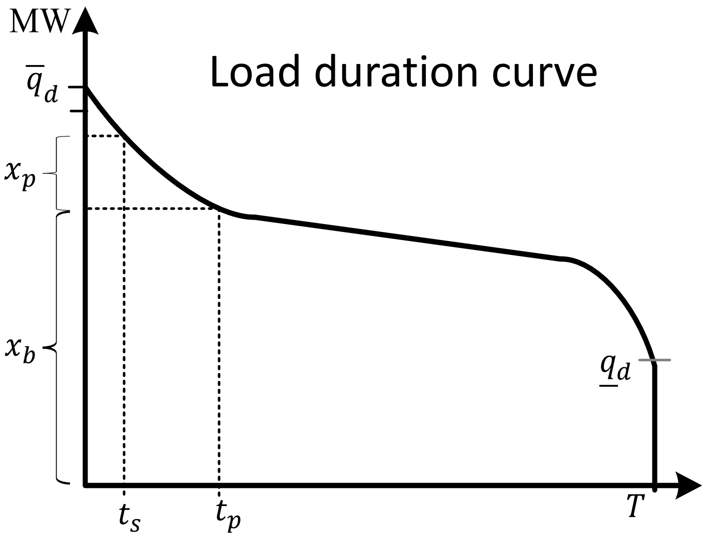
- Profit maximization gives the same result

$$\max \pi_i \Rightarrow \frac{\partial \pi_i}{\partial x_i} = 0$$

- Cost recovery is ensured in optimum

$$\pi_i = 0$$

System Optimality Conditions



t_s- duration of load shedding

t_p- duration of peaker operation

Peaker plant

$$\frac{\partial C}{\partial x_p} = F_p - (v_s - v_p) \cdot t_s$$

$$\frac{\partial C}{\partial x_p} = 0 \Rightarrow \boxed{t_s = \frac{F_p}{v_s - v_p}}$$

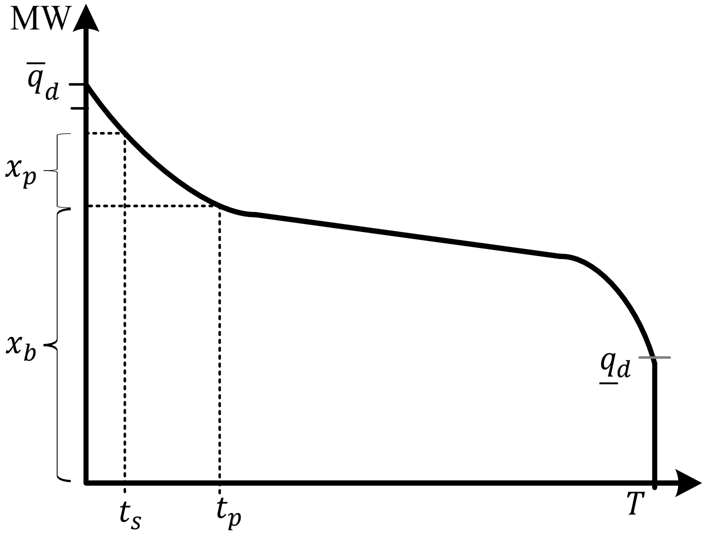
Baseload plant

$$\frac{\partial C}{\partial x_b} = F_b - (v_s - v_b) \cdot t_s - (v_p - v_b) \cdot (t_p - t_s)$$

$$\frac{\partial C}{\partial x_b} = 0 \Rightarrow \boxed{t_p = \frac{F_b - F_p}{v_p - v_b}}$$

Profit Maximization for Peaking Unit

$$\max_{x_p} \pi_{f,p} = \int_0^{t_p} \left(p(t) - v_p\right) q_{f,p}(t)dt - F_p x_{f,p} = \left(\left(v_s - v_p\right)t_s - F_p\right) x_{f,p}$$



$$\frac{\partial \pi_{f,p}}{\partial x_p} = 0 \Rightarrow \left(v_s - v_p\right)t_s - F_p = 0 \Rightarrow t_s = \boxed{\frac{F_p}{\left(v_s - v_p\right)}}$$

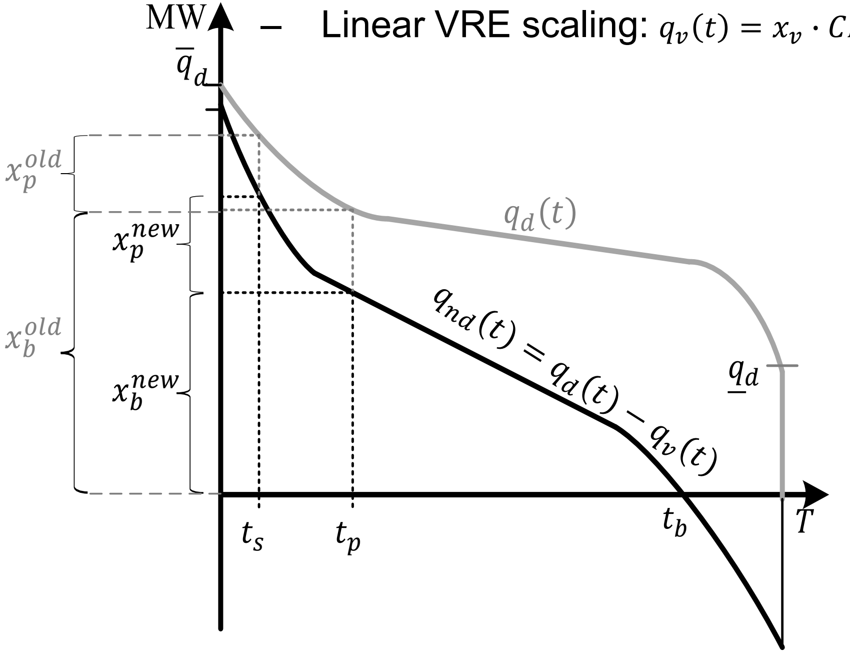
Same optimality condition as for system.

Cost recovery: $\pi_p = \left(v_s - v_p\right)t_s x_p - F_p x_p = 0$

The same holds true for the base plant.

Market Equilibrium with VRE

- Net load duration curve approach
  - e.g. Kennedy (2005)
  - Net demand: $q_{nd}(t) = q_d(t) - x_v \cdot CF_v(t)$
  - Linear VRE scaling: $q_v(t) = x_v \cdot CF_v(t)$



- t_s and t_p are independent of VRE level
  - Cost recovery for peak and base plants
- Base duration, t_b, must be determined
  - Cost recovery for VRE plant
- Introduction of VRE ($x_v > 0$) tends to give
  - Less baseplant capacity and energy
  - Slightly more peaker capacity
  - Slightly more load shedding
  - Some VRE curtailment

Optimality Conditions with VRE

- System optimality condition for the VRE plant given:

$$\frac{\partial C}{\partial x_v} = F_v - v_s AF_v^{[0,t_s]} t_s - v_p AF_v^{[t_s,t_p]} (t_p - t_s) - v_b AF_v^{[t_p,t_b]} (t_b - t_p)$$

$$\frac{\partial C}{\partial x_v} = 0 \Longrightarrow \quad t_b = t_p + \left(v_b AF_v^{[t_p,t_b]}\right)^{-1} \cdot \left(F_v - v_s t_s AF_v^{[0,t_s]} - v_p (t_p - t_s) AF_v^{[t_s,t_p]}\right)$$

- t_b gives the optimal VRE capacity from net demand duration curve

$$q_{nd}(t_b) = 0 \Rightarrow x_v$$

- Profit maximization gives same optimality conditions:

$$\pi_v = AR_v - AC_v = x_v \int_0^T p(t) AF_v(t) dt - F_v \cdot x_v \qquad \frac{\delta \pi_v}{\delta x_v} = 0 \Rightarrow F_v = \int_0^T p(t) AF_v(t) dt$$

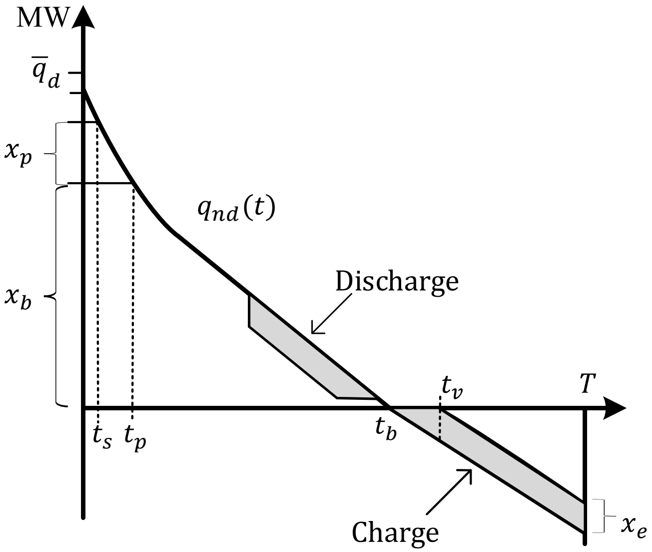
- Cost recovery of VRE plant also ensured, $\pi_v = 0$

Market Equilibrium with Energy Storage

- ES is challenging to include in duration curve modelling due to the energy storage level constraint
  - We can model power capacity limitation and efficiency explicitly, but not the energy storage constraint
  - Previous examples include Steffen and Weber (2013)

- We have derived optimality conditions for different EES operating assumptions
  - ES charging with «surplus» VRE energy only
    - Limited storage: Discharing only replaces base generation
    - Unlimited storage: Discharing at any time
  - General model with ES for price arbitrage across time periods

ES for Surplus VRE: Limited Storage

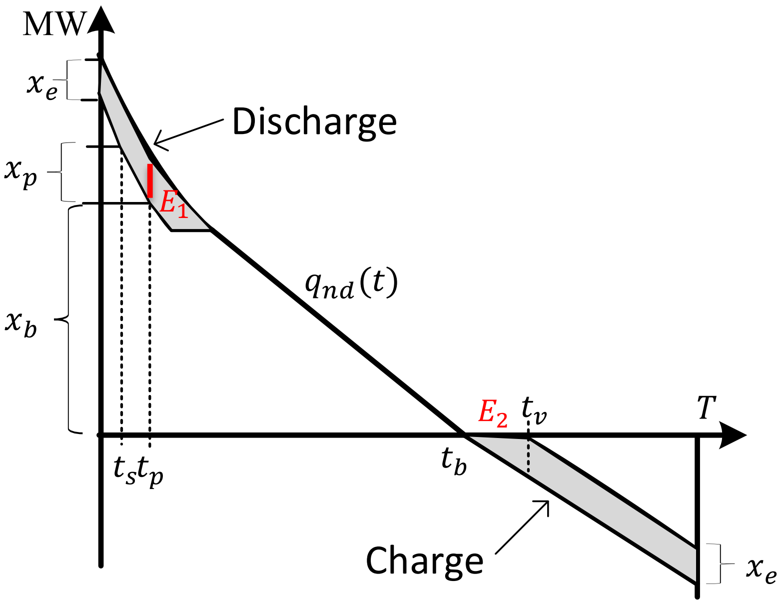


Optimality conditions for ES:

$$\eta_e v_b (T - t_v) = F_e$$

- Optimality condition for ES 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 increases the dispatch of VRE
- No change in thermal capacity, but less base dispatch

ES for Surplus VRE: Unlimited Storage



$$E_1 + x_e t_p = \eta_e E_2 + \eta_e (T - t_v)$$

Optimality conditions for ES:

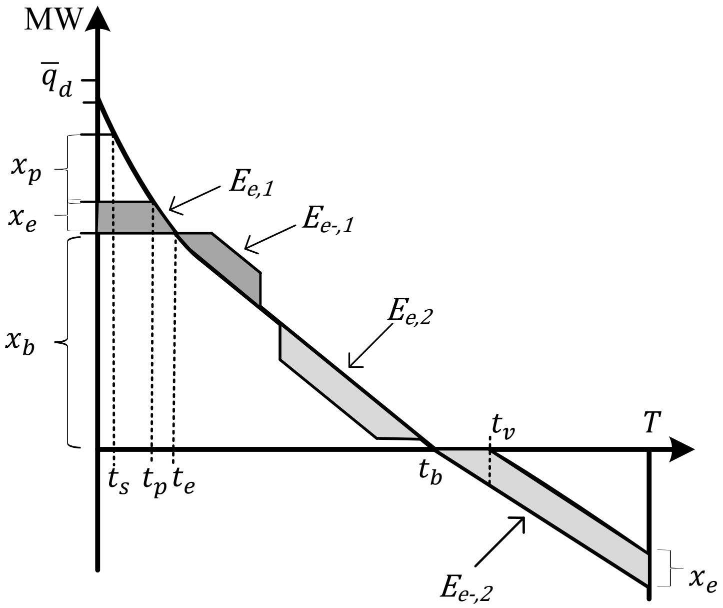
$$\frac{\partial C}{\partial x_e} = F_e - v_s t_s - v_p(t_p - t_s) - v_b \frac{\partial E_1}{\partial x_e} = 0$$

$$\frac{\partial C}{\partial x_e} = F_e - v_s t_s - v_p(t_p - t_s) - \eta_e v_b (T - t_v) + v_b t_p = 0$$

$$\eta_e v_b (T - t_v) = F_e - F_b$$

- Optimality conditions for VRE also changes
  - Lower base duration, t_b
- Introduction of ES increase VRE capacity, reduces thermal capacity

ES for General Price Arbitrage



- Indirect representation of storage limitation
  - ES stores VRE -> Replace Base
  - ES stores Base -> Replace Peak+Shedding

- Optimality condition for ES determines the duration of maximum charging and the duration of peaker
  - 4 non-linear equations with four unknowns
    - t_p, t_e, t_b, t_v

Insights from Analytical Model

- Profit maximization give same optimality conditions as system cost minimization
  - All plants recover their costs in system optimum
- Optimal VRE capacity always lead to some «excess» energy due to linear scaling
  - Exception: Optimal VRE capacity is zero
- Introducing unlimited ES for used for «excess» VRE energy triggers more installed VRE capacity in market equilibrium
- VRE and ES reduce average energy prices in equilibrium

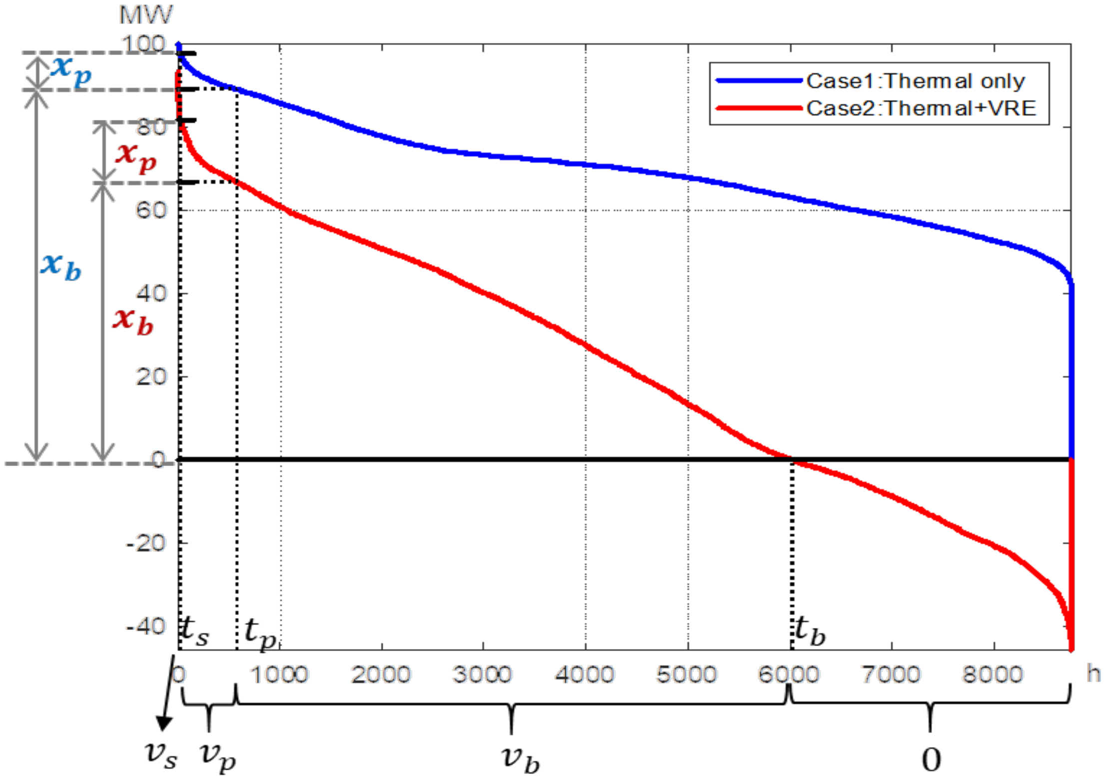
Numerical Example

- European aggregated hourly time series for 1 year
  - Wind and solar
  - Load scaled to 100MW
- Costs based on EU Commission reference Scenario 2050
  - Technology cost and plant data
  - Fuel and carbon prices
- Duration curve model based on optimality conditions for all plants
- YACEMOD* - LP with chronologial time series is used for validation

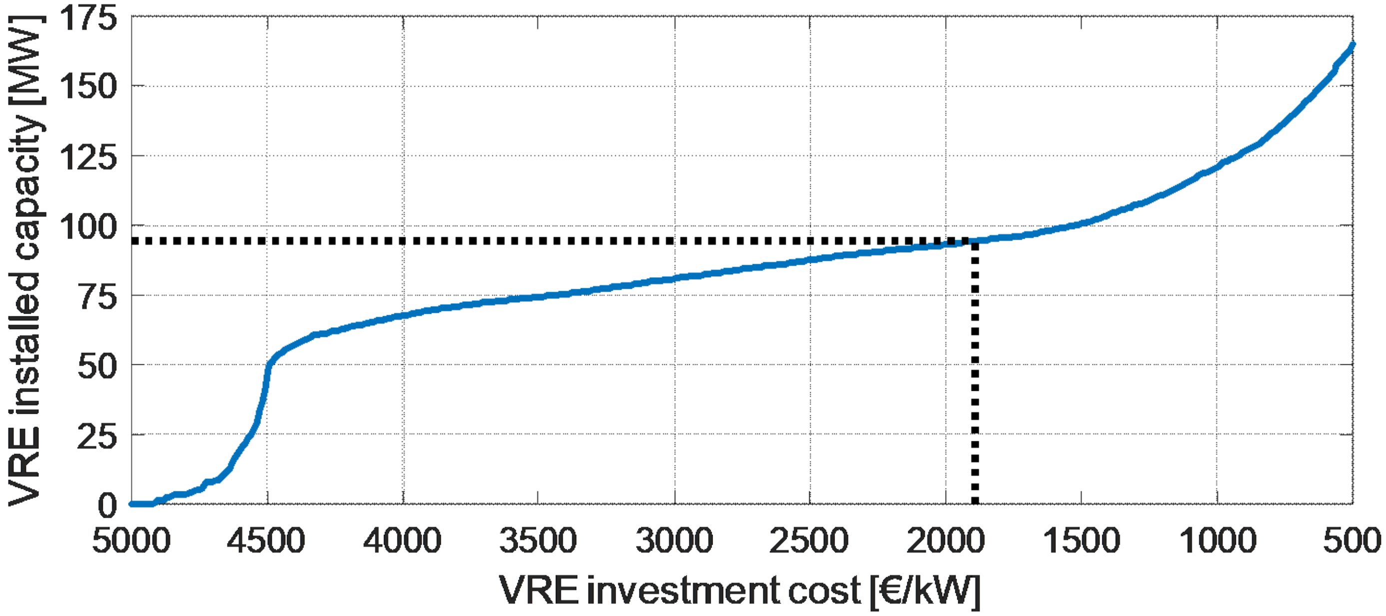
*Yet Another Capacity Expansion MODel

- Key assumptions
  - Peaker p: OCGT
  - Baseplant b: CCGT
  - VRE plant v: Offshore wind or solar PV
  - Energy Storage e: Li-Ion or Pumped hydro
  - Price during load shedding: 3000 $/MWh
- Three main cases
  - Case 1 - Base: Only peaker and baseplant
  - Case 2 - Add VRE
  - Case 3 - Add VRE and ES

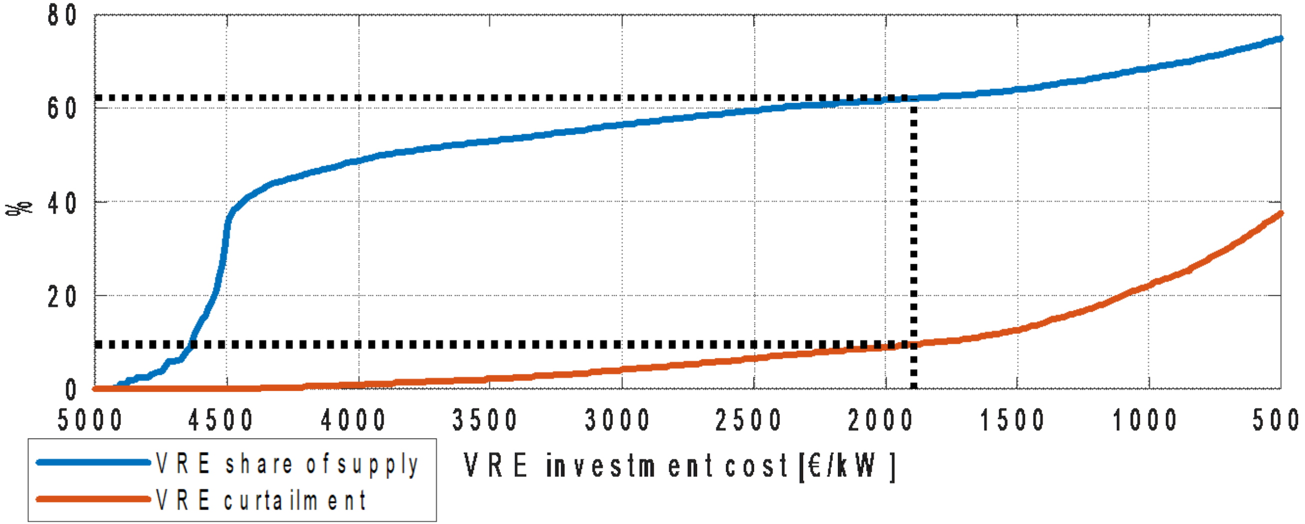
Load and Net Load Duration Curves



Installed Wind Capacity as a Function of Investment Cost

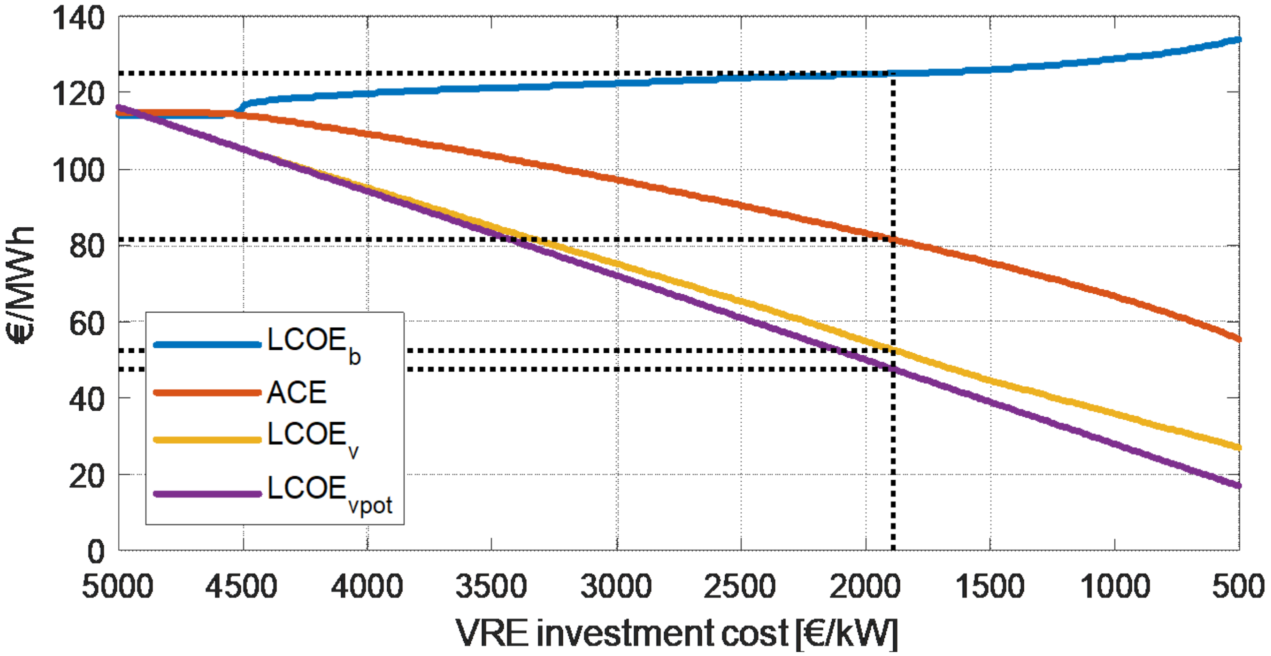


Saturation of Wind Penetration without ES

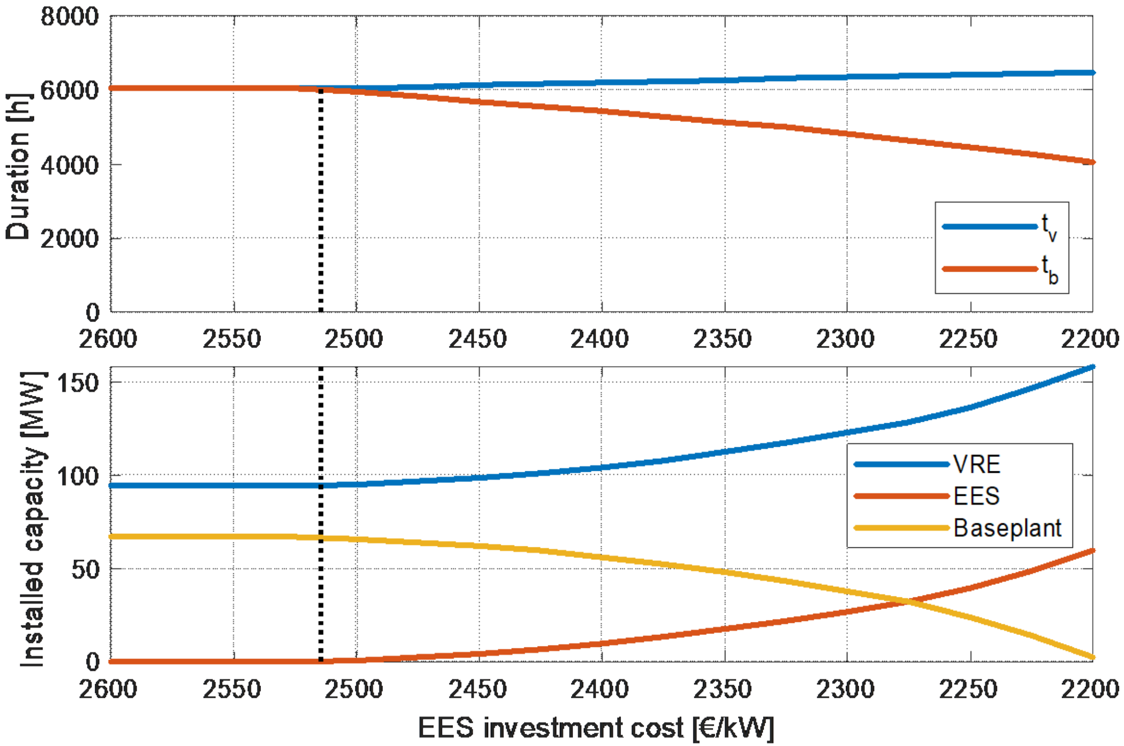


VRE Impacts on Electricity Costs

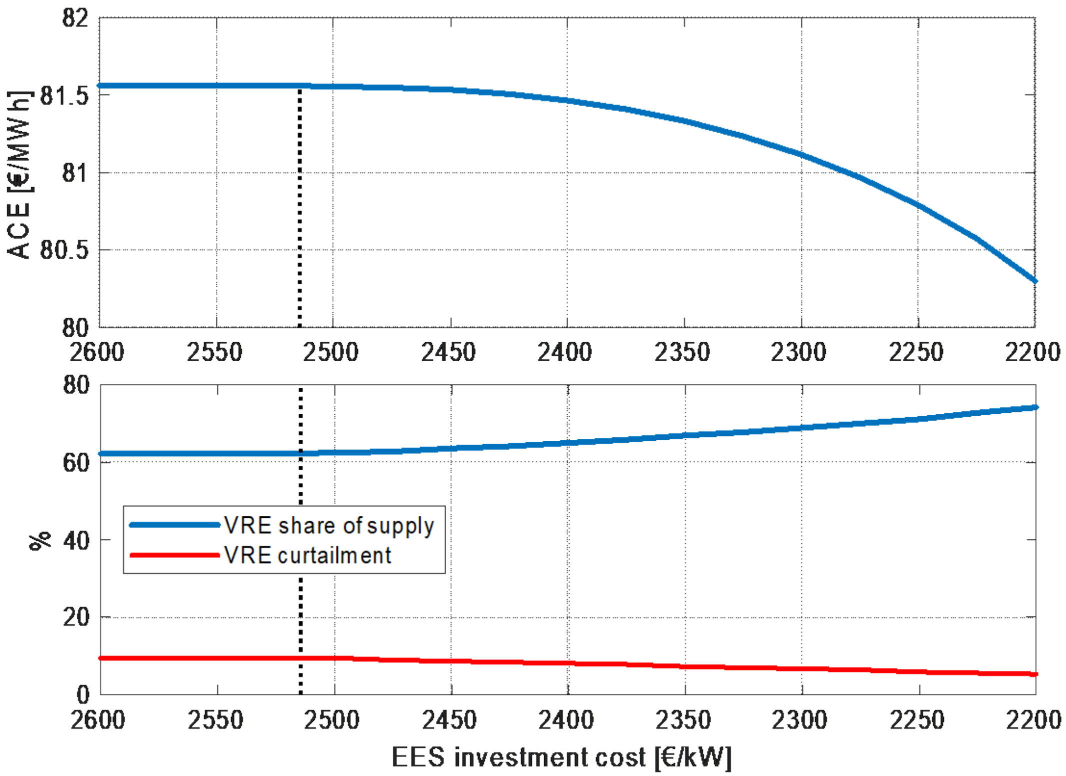
Average Electricity Costs (ACE) decreases as wind and solar becomes more competitive.



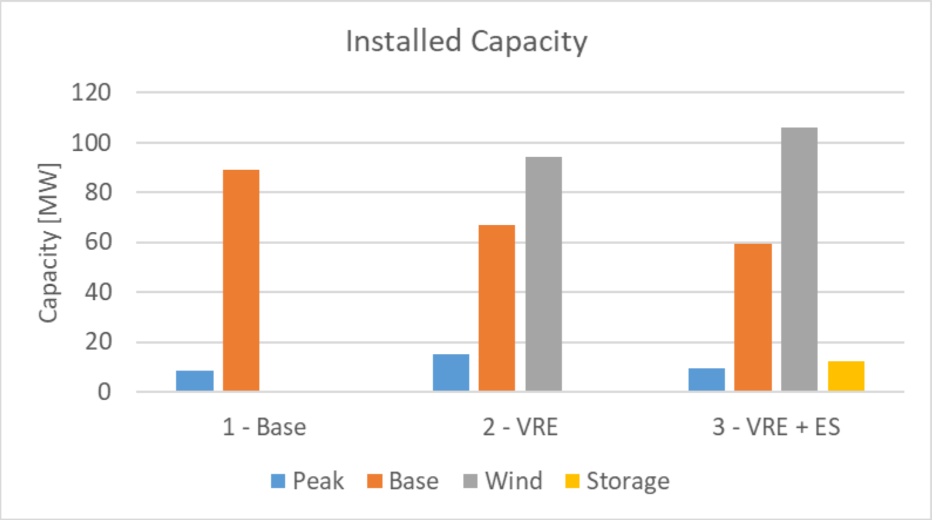
Adding Energy Storage



ES increases VRE; limited Cost Reduction



Summary of Results: Capacities and Prices



- VRE gives less base, more peak plants
- ES gives more VRE, less base and peak
- VRE and ES give much lower emissions

	1 - Base	2 - VRE	3 - VRE + ES
Weighted avg. price	114.9	81.6	81.4

All technologies break even in all cases

Conclusions

- All plants recover their costs in a perfect market with VRE and EES
  - Gives optimal generation mix to minimize system cost
  - The result is identical to profit mazimization of price-taker firms
  - ***Analytical and numerical analyses indicate that thermal generators, VRE, and ES can co-exist in regular energy-only markets***
- The merit-order effect of VRE changes the capacity mix so that all (remaining) generators recovers their costs
  - Just as when new, cheaper thermal generators enters the marked
- EES triggers more VRE capacity in equilibrium,
  - EES creates a new price segment based on the marginal value of storage, where the VRE gains additional profits.
- Theoretical model results are confirmed by standard generation expansion model (LP) with chronological time series inputs

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