Large-Scale Energy Storage Technologies: A study on private, social and welfare impacts for optimal policy design

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Motivation

- Solutions to mitigate the intermittency and variability associated with renewable energy

Energy Storage

- Excess energy is stored when demand is low and supplied when high
- High Cost

Demand Response

- Intentional modification of electricity consumption patterns

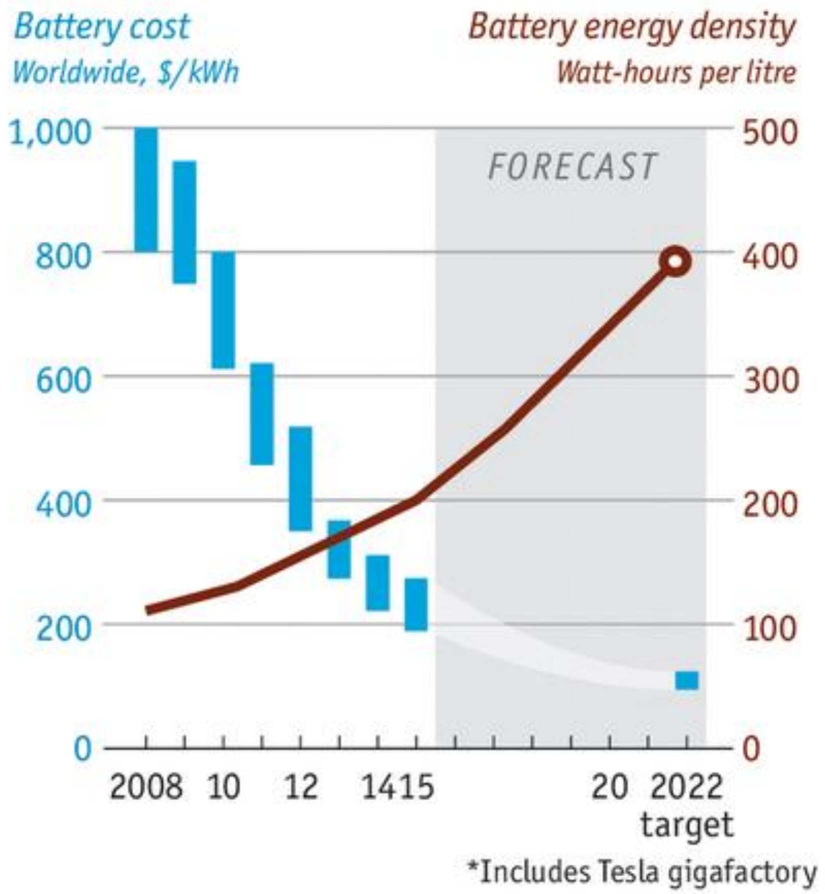
Micro-grids

- Autonomous grid, peer to peer trading

Motivation

Large-Scale Energy Storage

- Declining cost of batteries (lithium-ion)
- Stringent carbon emission policies

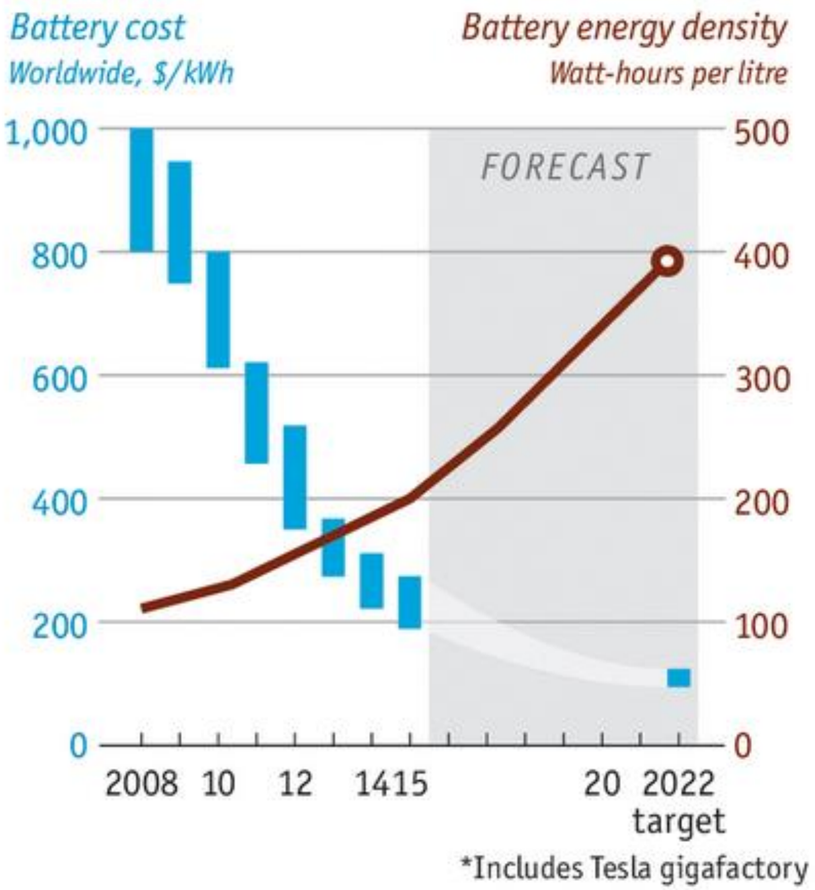


Source: The Economist

Motivation

Large-Scale Energy Storage

- Lack of regulations as well as lack of clarity (National Renewable Energy Laboratory, 2019)



Source: The Economist

Related Literature and contribution

- Literatures:
- (Denholm and Hand 2011) finds the amount of grid flexibility and storage that allows for various degree of RE penetrations, talks about hedging strategies that would help EST to have a competitive edge
- (McConnell, et al.2015) investigates the potential opportunities for price-taking energy storage device in energy-only electricity market in Australia.
- (Cutter, et al. 2014) feasibility of large-scale energy storage but assumes that storage does not affect price.
- (Carson, et al. 2012) " The private and social economics of bulk electricity storage"
- (Sioshansi, 2010) "Welfare Impacts of Electricity Storage and the Implications of Ownership structure"
- (Zafirakis, et al.2014) "Modeling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy"

Related literature and Contribution

- Not many papers on policy instruments to support this technology
- Impact on wholesale electricity price
- Impact on the value of RE and emissions

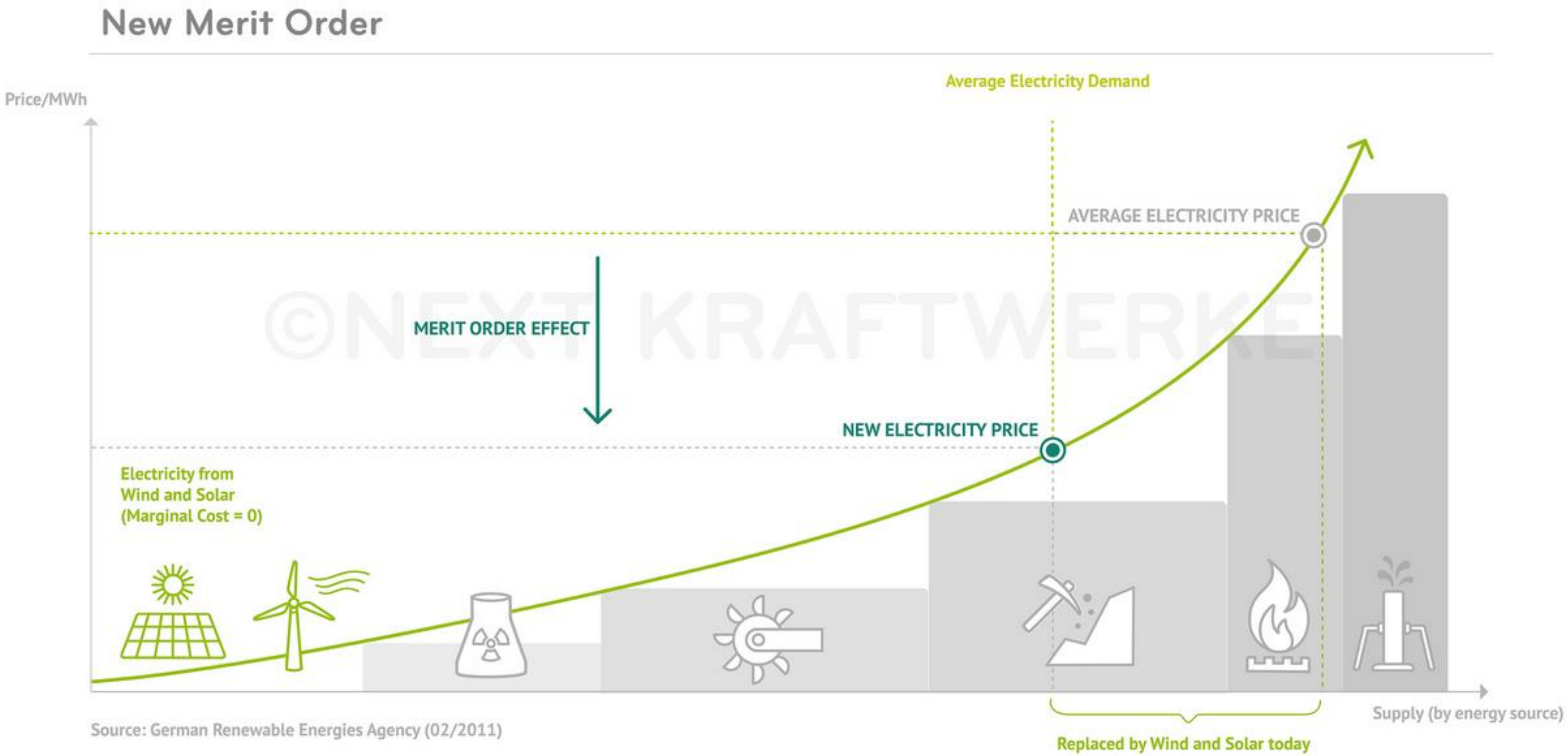
Research Questions

- Policy Instruments that would be required for the EST to enter the market?
    - Cost-benefit model

- What would be the welfare maximizing size of storage?
    - Optimal size (benchmark for empirical analysis)

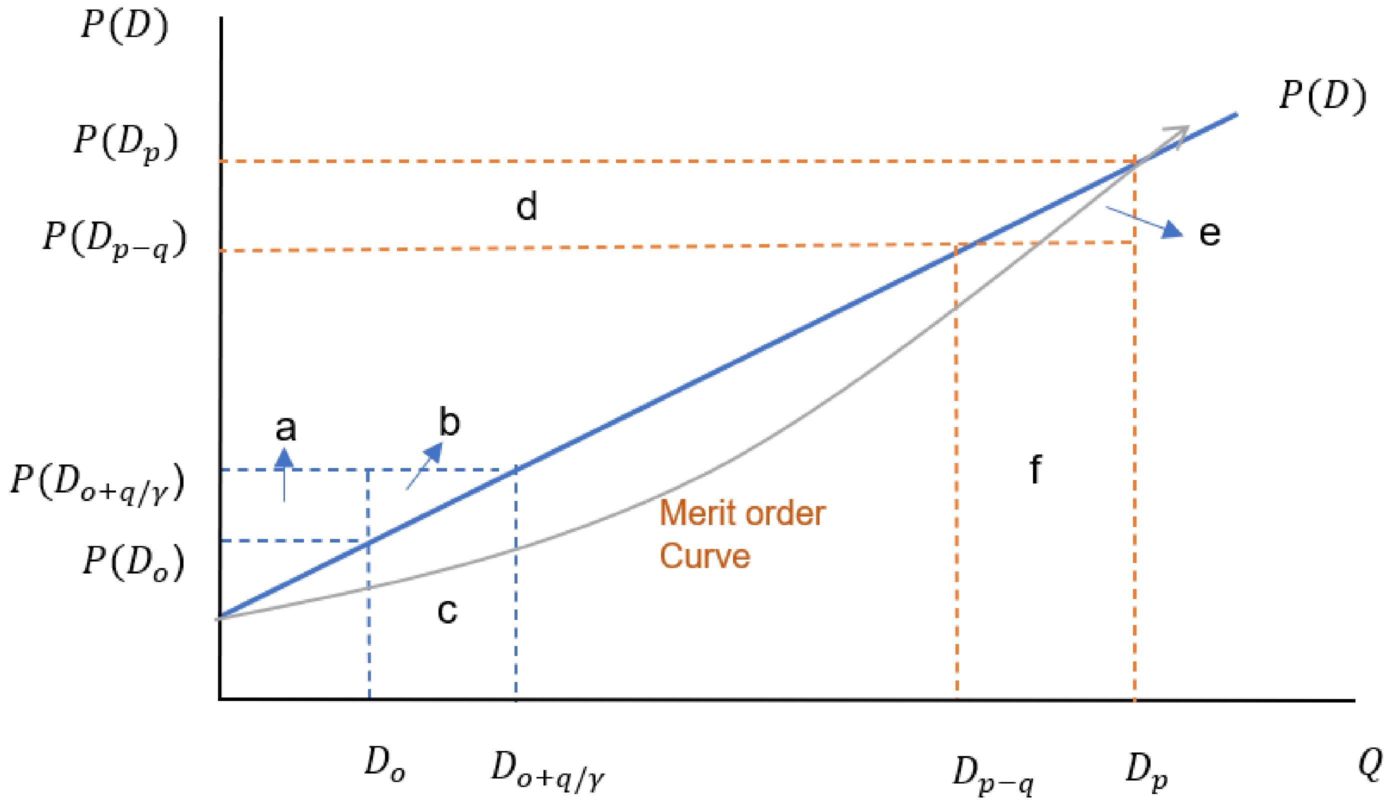
- What are the impacts of storage on the value of renewable electricity and environmental emissions?
    - Quantify the indirect impacts to assess the benefits

Conceptual Framework



Source: German Renewable Energies Agency (02/2011)

Conceptual Framework



- Two Period Model
    - Peak (p) and Off-Peak (o)
- $P(D) = C_f + C_m D$
- These changes in prices and the amount of energy will result in welfare changes for consumers and generators, as well as storage operators.

Welfare Impacts of storage

- Storage Operators Profit (π_s) $\emptyset = 1/\gamma$

$$\pi_s = qP\left(D_{p-q}\right) - \emptyset qP(D_{o+q/\gamma}) \quad = q\left[C_f(1-\emptyset) + C_m\left(D_p - \emptyset D_o\right)\right] - q^2 C_m(1+\emptyset^2)$$

- Producer Surplus (PS)

$$\Delta PS = \int_{D_{p-q}}^{D_p} P(Q)dQ - \int_{D_o}^{D_{o+q/\gamma}} P(Q)dQ \quad = qC_m\left(\emptyset D_o - D_p\right) + \frac{1}{2}q^2 C_m(1+\emptyset^2)$$

- Consumer Surplus(CS)

$$\Delta CS = \left(P\left(D_p\right) - P\left(D_{p-q}\right)\right)D_p - (P\left(D_{o+q/\gamma}\right) - P(D_o))D_o \quad = qC_m(D_p - \emptyset D_o)$$

- Social Welfare (SW)

$$\Delta SW = \pi_s + \Delta PS + \Delta CS \quad = q\left[C_f(1-\emptyset) + C_m\left(D_p - \emptyset D_o\right)\right] - \frac{1}{2}q^2 C_m(1+\emptyset^2)$$

Socially optimal vs Profit maximizing (q)

- Storage operators have incentives to underproduce $q^* < q^*(SO)$

$$q^* = \begin{cases} 0, & if\ q^* \leq 0 \\ \bar{q}, & if\ q^* \geq \bar{q} \\ \dfrac{C_f(1-\emptyset)+C_m\left(D_p-\emptyset D_o\right)}{2.\,C_m(1+\emptyset^2)} & if\ \ q^* \leq \bar{q} \end{cases}$$

$$q^*(SO) = \begin{cases} 0, & if\ q^* \leq 0 \\ \bar{q}, & if\ q^* \geq \bar{q} \\ \dfrac{C_f(1-\emptyset)+C_m(D_H-\emptyset D_L)}{C_m(1+\emptyset^2)} & if\ \ q^* \leq \bar{q} \end{cases}$$

Impacts on the value of Renewable electricity

$$\Delta PS(Ren) = (P\left(D_p\right) - P\left(D_{p-q}\right) + P\left(D_{o+q/\gamma}\right) - P(D_o))Q_{Ren}$$

$$\frac{\Delta \mathrm{PS(Ren)}}{\Delta \mathrm{q}} = \left(\frac{\partial P(D_{o+q/\gamma})}{\partial q} - \frac{\partial P\left(D_{p-q}\right)}{\partial q}\right) Q_{Ren}$$

Impact on the value of renewable electricity

- Case I: Low penetration of RE in the generation mix

$$\text{Total cost avoided}(TC) = \underbrace{C_g(D_o) + C_g(D_p)}_{\text{Cost of generation from conventional sources}} + \tau\underbrace{\{e(D_p) + e(D_o)\}}_{\text{Environmental cost from conventional sources}}$$

$$\text{Marginal Social Benefit}\ (MSB(Q_{Ren})) = -\frac{\partial TC}{\partial Q_{Ren}}$$

$$MSB(R) = P(D_o).q_{Ro} + P(D_p).q_{Rp} \longrightarrow \text{Competitive Market : } P(D_o) = C'_G(D_o)$$

$$\frac{\partial MSB(R)}{\partial q} = \frac{\partial P(D_o)}{\partial q}\emptyset q_{Ro} - \frac{\partial P(D_p)}{\partial q} q_{Rp}$$

$$\frac{\partial P(D_p)/\partial q}{\partial P(D_o)/\partial q} < \frac{\emptyset q_{Ro}}{q_{Rp}} \longrightarrow$$

Arbitrage will reduce the value of renewables that produces heavily during the peak period

Impact on Renewable Energy Generation

- Case II: High penetration of RE in the generation mix (curtailment cost)Conventional Generation(Peak demand)

$$Total\ cost\ (TC) = C_G(D_p)$$

$$MSB(R) = C'_G(D_p).\,q_{Rp}$$

$$\frac{\partial MSB(R)}{\partial q} = \frac{\partial C'_{CC}(D_o)}{\partial q} \emptyset q_{Ro} - \frac{\partial P(D_p)}{\partial q} q_{Rp}$$

→ Arbitrage will increase the value of renewables if the curtailment cost is high enough

Impact on Environmental Emissions

- Case I:Low RE

$$MSB(R) = \tau\{e'(D_p).\,q_{Rp} + \gamma e'(D_o).\,\emptyset q_{Ro}\}$$

$$\frac{\partial MSB(R)}{\partial q} = \tau\left\{\frac{\partial e'(D_o)}{\partial q}.\,\emptyset q_{Ro} - \frac{\partial e'(D_p)}{\partial q}.\,q_{Rp}\right\}$$

→ Ambiguous impact on the environmental benefit

- Case II: High RE

$$MSB(R) = \tau\{e'(D_p).\,q_{RP}\}$$

$$\frac{\partial MSB(R)}{\partial q} = \tau\left\{-\frac{\partial e'(D_p)}{\partial q}.\,q_{Rp}\right\}$$

→ Storing electricity during off peak period will reduce emissions

Determination of optimal policy

Break Even FIT (Feed in Tariff)

$$Total\ Benefit/kwh = C'_G(D) + C'_{CC}(R) + \tau\big(e(D)\big)$$

Avoided fuel cost

Avoided curtailment cost

Avoided emission cost

$$Total\ Costs/Kwh = P_{ICS}(Q) + P(D)$$

ICS= Initial cost subsidy

$$(Net\ Benefit)/Kwh = Total\ Benefit - Total\ \ costs$$

Application to Electricity Market (In progress)

- Data from ERCOT, Texas
- Data from CAISO, California
- Lithium Ion Batteries

Conclusions

- Incentive to underproduce
- Not a simple relationship between RE and emissions
- Case specific
- BEFIT- “Socially Just” FIT policy

Further Research

- Bidding strategy of competing firms
- Ownership structure

Questions?

Thank you