Electricity grid and storage – complements or substitutes?

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Introduction
“To manage and coordinate the transition processes that present power systems are facing during the next decades, it will be crucial to gain a better understanding of how single elements of these systems (e.g. generation, transmission, and storage facilities) interact with each other [...]”

Haller et al. (2012a, p. 8).
Background electricity system

Public / scientific debate: Can additional storage capacity substitute transmission capacity?
Literature review

Storage and transmission capacities are...

Substitutes
- Denholm and Sioshansi (2009), MacDonald et al. (2016), Zhou et al. (2014)
  Barton and Infield (2004), Sioshansi et al. (2012), Haller et al. (2012b)

Independent / ambiguous
- Steinke et al. (2013), Brancucci Martinez-Anido and de Vries (2013)

Complements
- Haller et al. (2012a)

BUT: All are single example numeric / empiric studies; only a spotlight on the issue

Research question

Under which conditions are storage and transmission capacities complements or substitutes?
Methods
General model setup

- Two locations $i \in (1, 2)$
- Two time periods ($t \in \text{peak, off-peak}$)
- Price inelastic, deterministic, residual demand
- Rising marginal costs for generation
  No capacity restriction or additional costs
- Storage and transmission may shift power in time and space
  Constant marginal costs for storage and grid power capacities (kW)
- Round trip efficiency losses for storage

→ Find cost efficient dispatch and capacities
The model equations

- Residual load
- Energy balance for conventional supply
- Transmission capacity
- Transmission dispatch
- Storage power capacity
- Storage dispatch
- Storage round trip efficiency $\eta$
- Long term costs

$$C = \sum_{i,t} c(x_{i,t}) + \psi(K_1 + K_2) + yL$$

- Cross derivatives

$$\frac{\partial^2 C}{\partial K \partial L} = \frac{\partial C}{\partial K} \frac{\partial C}{\partial L}$$

- Complements
  - $\frac{\partial^2 C}{\partial K \partial L} < 0$
  - $\frac{\partial C}{\partial K} > 0$
- Independent
  - $\frac{\partial^2 C}{\partial K \partial L} = 0$
- Substitutes
  - $\frac{\partial^2 C}{\partial K \partial L} > 0$
Storage-transmission interdependence

- Assumptions
  - \( i = 1 \rightarrow \) high demand location, \( i = 2 \rightarrow \) low demand location
    \[
    \forall \tau : \quad R_{1,\tau} \geq R_{2,\tau} \quad c_{1,\tau}^l \geq c_{2,\tau}^l \quad z_\tau \geq 0
    \]
  - Linearly rising marginal costs
    \[
    c_{i,\tau}^\prime \rightarrow const.
    \]

- Cross derivatives determine interdependence
  - Inserting feasible results for \( K_i, L \)
    \[
    i = 1 : \quad \frac{\partial^2 C}{\partial K_1 \partial L} = \sum_\tau \left[ \left( \frac{\partial y_{1,\tau}}{\partial K_1} - \frac{\partial y_{1,\tau}^-}{\partial K_1} \right) \left( -\frac{\partial z_\tau}{\partial L} \right) c_{1,i,\tau}'' \right]
    \]
    \[
    i = 2 : \quad \frac{\partial^2 C'}{\partial K_2 \partial L} = \sum_\tau \left[ \left( \frac{\partial y_{2,\tau}}{\partial K_2} - \frac{\partial y_{2,\tau}^-}{\partial K_2} \right) \frac{\partial z_\tau}{\partial L} c_{2,i,\tau}'' \right]
    \]
Solving the optimization problem

Minimize total power system costs

Twofold problem:

• Solving the dispatch (operation decision for given capacity)

• Solving capacity decision

\[
\max_{x_{i,\tau}, z_{\tau}, y_{1,\tau}, y_{1,-\tau}, K_i, L} \quad C = - \sum_{i} \left[ \sum_{\tau} c(x_{i,\tau}) + \psi K_i \right] - \gamma L
\]

s.t.:

\[\forall \tau : R_{1,\tau} - x_{1,\tau} + y_{1,\tau}^+ - y_{1,-\tau} - z_{\tau} = 0\]

\[\forall \tau : R_{2,\tau} - x_{2,\tau} + y_{2,\tau}^+ - y_{2,-\tau} + z_{\tau} = 0\]

→ Energy balance constraint

\[\forall \tau : |z_{\tau}| - L \leq 0 \begin{cases} z_{\tau} - L \leq 0 & \text{for } z_{\tau} \geq 0 \\ -z_{\tau} - L \leq 0 & \text{for } z_{\tau} < 0 \end{cases}\]

→ Transmission capacity constraint

\[\forall \tau, i : y_{i,\tau}^+ + y_{i,-\tau} - K_i \leq 0\]

→ Storage capacity and efficiency constraint
Optimal storage and transmission capacities

- Storage capacity

\[ \frac{\partial L}{\partial K_i} = -\psi < 0 \quad K_i^* = 0 \quad \text{or} \quad \frac{\partial L}{\partial K_i} = -\psi + \eta c_{i,p} - c_{i,o} \leq 0 \quad K_i^* > 0 \]

- Transmission capacity

\[ \frac{\partial L}{\partial L} = -\gamma < 0 \quad L^* = 0 \quad \text{or} \quad \frac{\partial L}{\partial L} = -\gamma + |c_{1,o}' - c_{2,o}'| \quad \text{or} \quad -\gamma + |c_{1,p}' - c_{2,p}'| \leq 0 \]

\[ \gamma = |c_{1,o}' - c_{2,o}'| \text{ (or } \gamma = |c_{1,p}' - c_{2,p}'|) \]

No transmission

Transmission constrained in one period

\[ z_p = L \quad \text{or} \quad z_o = L \]

Transmission constrained in both periods

\[ z_p = L \quad \text{and} \quad z_o = L \]
Results
Storage-transmission interdependence

- Transmission peak load restriction \( (z_p = L, \ z_o < L) \)
  
  **Substitutes** \( \frac{\partial^2 C}{\partial L \partial K_1} = \eta c''_{1,p} > 0 \)  
  
  **Complements** \( \frac{\partial^2 C}{\partial L \partial K_2} = -\eta c''_{2,p} < 0 \)  

- Transmission off-peak load restriction \( (z_p < L, \ z_o = L) \)
  
  **Complements** \( \frac{\partial^2 C}{\partial L \partial K_1} = -c''_{1,o} < 0 \)  
  
  **Substitutes** \( \frac{\partial^2 C}{\partial L \partial K_2} = c''_{2,o} > 0 \)  

- Full restriction of transmission \( (z_p = z_o = L), \ \eta < 1 \)
  
  **Complements** \( \frac{\partial^2 C}{\partial L \partial K_1} = \eta c''_{1,p} - c''_{1,o} < 0 \)  
  
  **Substitutes** \( \frac{\partial^2 C}{\partial L \partial K_2} = c''_{2,o} - \eta c''_{2,p} > 0 \)  

High demand area  
Low demand area

Aggregate effect
\[
\sum_i \frac{\partial^2 C}{\partial L \partial K_i} = 0
\]
Results summary

<table>
<thead>
<tr>
<th>Transmission restriction</th>
<th>Storage location</th>
<th>High demand ($K_1$)</th>
<th>Low demand ($K_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak load</td>
<td>S</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Off-peak load</td>
<td>C</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Full</td>
<td>C</td>
<td></td>
<td>S</td>
</tr>
</tbody>
</table>

Efficient storage locations in bold
Results intuition

With additional transmission the difference in marginal generation costs $c'(x_{i,p}) - c'(x_{i,o})$

- increases for storage in region 1 $\rightarrow$ complements
- decreases for storage in region 2 $\rightarrow$ substitutes
- increases for storage in region 2 $\rightarrow$ complements
- decreases for storage in region 1 $\rightarrow$ substitutes
- does not change
- Effect depends on valuation of efficiency losses
Discussion & Conclusion
Discussion

• Model also applicable for different storage-transport problems

• Critical assumptions:
  – Only 2 locations, 2 periods and 1 storage round trip
  – Cost minimizing approach
  – No decision about capacity of generation, RES, demand side management

• Simplistic approach well suited
  → clear conditions for storage transmission relation can be formulated
  – Implications of some simplifications remain to be checked

• Consistency with previous studies (e.g. Haller et al. 2012a, Zhou et al. 2014, Denholm and Sioshansi 2009) is difficult to evaluate
  – Variations in assumptions and methods
  – Lack in information (Storage location, transmission restriction)
  → No clear contradictions
Conclusion

• Storage and transmission can act as complements OR substitutes depending on
  1. Storage location
  2. Occurrence of transmission restriction
  3. Cost structure of generation (merit order curve)

• Policy advice:
  – Storage may ensure a relief of the transmission grid
    BUT: dependent on choice of location – incentive policy could be desirable

• Future work:
  – Effects of pricing schemes and renewable energies
  – Multiple node model with loop flows
  – Bridging to real world setup (e.g. by model calibration)
References I


References II


Thank you