Strategic Use of Storage: The Impact of Carbon Policy, Resource Availability, and Technology Efficiency on a Renewable-Thermal Power System

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Introduction
Is Energy Storage the Answer?
Role of Flexible Generation

- Marginal costs: €20-22/MWh (lignite-coal), €30/MWh (CCGT), €45/MWh (gas)
- Daily prices: €24.1/MWh and €43.5/MWh
- *Residual load = buy volume - wind - solar
Equilibrium Analysis of Storage

- Crampes and Moreaux (2001) show theoretically how market power may lower water value and even render it negative.
- Bushnell (2003) finds empirical support via a complementarity analysis of the California hydro-thermal system.
- Restructuring and sustainable transition enhance hydropower producers’ incentives to shift generation between peak and off-peak periods (Mathiesen et al., 2013).
- Sioshansi (2010) analyses the welfare impacts of storage use via a stylised partial-equilibrium model with perfectly competitive electricity generation.
- Sioshansi (2014) demonstrates when storage can reduce social welfare.
- In the context of transmission capacity, Downward et al. (2010) examine how a carbon tax may actually increase emissions in the presence of market power.
Evolving Paradigms

**Vertical Integration**
- Generation
- Distribution
- Retailing
- Transmission

**Restructuring**
- Gen. 1
- Ret. 1
- Gen. n
- Ret. m

- Distribution
- Transmission
Playing Games

**Equilibrium Problem (EP)**

Optimisation Problem 1
...
Optimisation Problem n

Equilibrium Constraints

**Complementarity Problem (CP)**

KKT Conditions of Problem 1
...
KKT Conditions of Problem n

Equilibrium Constraints

**Optimisation Problem constrained by Optimisation Problems (OPcOP)**

Objective Function
Constraints
Optimisation Problem 1
...
Optimisation Problem n
Equilibrium Constraints

**Mathematical Program with Equilibrium Constraints (MPEC)**

Objective Function
Constraints
KKT Conditions of Problem 1
...
KKT Conditions of Problem n
Equilibrium Constraints
Research Objective and Findings

- How are storage operations, producer profit, and social welfare affected by market power, carbon policy, and device efficiency?
- Bushnell (2003)’s main findings about more off-peak RE production and a negative marginal value of RE storage under market power hold for only a low level of the carbon tax
  - Moreover, a carbon tax may actually increase peak thermal production under perfect competition
- Greater storage efficiency monotonically decreases marginal value of RE storage under market power but has a non-monotonic effect under perfect competition
  - RE producer profits from a ceteris paribus increase in the efficiency of an inefficient device but a “turning point” when the device is so efficient that the peak price is actually depressed
  - Social welfare increases monotonically with device efficiency
  - Conflict between private and social incentives can be partially resolved through a carbon tax
Mathematical Formulation
Assumptions

- Two periods, $j = 1, 2$, that correspond to off- and on-peak, respectively
- No uncertainty or transmission constraints
- Equilibrium model with a (i) storage-enabled renewable-energy (RE) and (ii) thermal producer
  
  $P_j(x_j + y_j) = A_j - (x_j + y_j) \text{ [in }$/MWh$]$,
  
  where $A_2 > A_1 > 0$

- RE production incurs no explicit cost, but available stock of RE capacity is $D \geq 0$ [in MWh] and $x_1 + Fx_2 = D$, where $F \geq 1$

- Thermal cost function $\frac{1}{2}Cy_j^2 \text{ [in }$/MWh$]^2$, where $C > 0$ [in $$/MWh^2$] with emission rate $R > 0$ [in t/MWh] and carbon tax $T$ [in $$/t$]

- For interior solutions, require (i) $A_2 > FA_1$ and (ii) $C > 3 - 2\sqrt{2} \approx 0.17$
RE Producer

- RE producer’s problem is to maximise its profit over the two periods consisting of revenue from sales subject to its resource availability

\begin{align*}
\text{Maximise}_{x_j \geq 0} & \quad [A_1 - (x_1 + y_1)] x_1 + [A_2 - (x_2 + y_2)] x_2 \\
\text{s.t.} & \quad x_1 + F x_2 = D : \mu
\end{align*}

- $\mu$ [in $$/\text{MWh}$$] is the dual variable on the RE resource constraint representing the marginal value of RE storage

- Since (1)–(2) is a convex optimisation problem, it may be replaced by its Karush-Kuhn-Tucker (KKT) conditions for optimality:

\begin{align*}
0 \leq x_1 & \quad \perp - [A_1 - (2x_1 + y_1)] + \mu \geq 0 \\
0 \leq x_2 & \quad \perp - [A_2 - (2x_2 + y_2)] + F \mu \geq 0 \\
\mu \text{ free} & \quad D - x_1 - F x_2 = 0
\end{align*}
Thermal producer’s problem is to maximise its total profit, which consists of sales revenue, generation cost, and CO$_2$ taxes:

\[
\text{Maximise } \sum_{j \geq 0} \left[ A_1 - (x_1 + y_1) \right] y_1 + \left[ A_2 - (x_2 + y_2) \right] y_2 - \frac{1}{2} C \left( y_1^2 + y_2^2 \right) - TR (y_1 + y_2)
\]  

(6)

Since (6) is a convex optimisation problem, it may be replaced by its KKT conditions for optimality:

\[
0 \leq y_1 - [A_1 - (2y_1 + x_1)] + Cy_1 + TR \geq 0 
\]  

(7)

\[
0 \leq y_2 - [A_2 - (2y_2 + x_2)] + Cy_2 + TR \geq 0 
\]  

(8)
Perfect Competition

\[ x_{1}^{PC} = \frac{F (FA_1 - A_2) + D + F (F - 1) RT/C}{1 + F^2} \]  \hfill (9)

\[ x_{2}^{PC} = \frac{A_2 - FA_1 + FD - (F - 1) RT/C}{1 + F^2} \]  \hfill (10)

\[ y_{1}^{PC} = \frac{A_1 + FA_2 - D - F (F - 1) RT/C - (1 + F^2) RT}{(1 + F^2) (C + 1)} \]  \hfill (11)

\[ y_{2}^{PC} = \frac{F (A_1 + FA_2 - D) + (F - 1) RT/C - (1 + F^2) RT}{(1 + F^2) (C + 1)} \]  \hfill (12)

\[ \mu^{PC} = \frac{C (A_1 + FA_2 - D) + (F + 1) RT}{(1 + F^2) (C + 1)} \]  \hfill (13)
Cournot Oligopoly

\[ x_{CO}^1 = \frac{F (FA_1 - A_2) (C + 1) + F (F - 1) RT}{(1 + F^2) (2C + 3)} + \frac{D}{1 + F^2} \]  \quad (14)

\[ x_{CO}^2 = \frac{(A_2 - FA_1) (C + 1) - (F - 1) RT}{(1 + F^2) (2C + 3)} + \frac{FD}{1 + F^2} \]  \quad (15)

\[ y_{CO}^1 = \frac{(2C + 3) A_1 + F^2 (C + 2) A_1 + F (C + 1) A_2 - (2C + 3) D}{(1 + F^2) (C + 2) (2C + 3)} \]
\[ - \frac{[2C + 3 - F + F^2 (2C + 4)] RT}{(1 + F^2) (C + 2) (2C + 3)} \]  \quad (16)

\[ y_{CO}^2 = \frac{F (C + 1) A_1 + (C + 2) A_2 + F^2 (2C + 3) A_2 - F (2C + 3) D}{(1 + F^2) (C + 2) (2C + 3)} \]
\[ - \frac{[2C + 4 - F + F^2 (2C + 3)] RT}{(1 + F^2) (C + 2) (2C + 3)} \]  \quad (17)

\[ \mu_{CO} = \frac{(C + 1) A_1 + F (C + 1) A_2 - (2C + 3) D + (F + 1) RT}{(1 + F^2) (C + 2)} \]  \quad (18)
### Interior Solution Definitions

**Definition**

The interior solution set for perfect competition is defined as

$$
\mathcal{S}_{PC} = \{(x, y)_{PC} \in \mathbb{R}^4_+ | x^P_{PC} > 0, y^P_{PC} > 0, j = 1, 2 \}
$$

(19)

**Definition**

The interior solution set for Cournot oligopoly with $\mu < 0$ is defined as

$$
\mathcal{S}_{\mu \ CO} = \{(x, y)^{CO}_{\mu} \in \mathbb{R}^4_+ | \mu^{CO} < 0, x^{CO}_j > 0, y^{CO}_j > 0, j = 1, 2 \}
$$

(20)
Perfect Competition
Perfect Competition

Lemma

$S^{PC}$ is non-empty if and only if

\[(i) \quad D > F \left( A_2 - FA_1 - (F - 1) \frac{RT}{C} \right) \quad \text{if} \quad RT \leq \frac{C(A_2 - FA_1)}{F - 1} \tag{21a} \]

\[(ii) \quad D > \frac{-A_2 + FA_1 + (F - 1)RT/C}{F} \quad \text{if} \quad RT > \frac{C(A_2 - FA_1)}{F - 1} \tag{21b} \]

\[(iii) \quad D < A_1 + FA_2 - F(F - 1) \frac{RT}{C} - (1 + F^2)RT \tag{21c} \]

\[(iv) \quad RT < \min \left\{ A_1, \frac{A_2}{F + \frac{F - 1}{C}} \right\}. \tag{21d} \]

Furthermore, $\mu^{PC} > 0$ is in $S^{PC}$. 
Cournot Oligopoly

\[
\frac{(C+1)(A_2-FA_1)}{F-1}
\]

\[
\frac{A_1}{2}
\]

\[
0
\]

\[
D
\]

\[
\frac{(A_1+FA_2)(C+1)}{2C+3}
\]

\[
\frac{A_1(F+1)^2+(A_1+FA_2)(C+1)}{2C+3}
\]
Cournot Oligopoly

Lemma

\( S^\text{CO}_\mu \) is non-empty if and only if

\[
(i) \quad D > \frac{(C + 1)(A_1 + FA_2) + RT(1 + F)}{2C + 3} \\
(ii) \quad D < \frac{A_1(C + 2)(1 + F^2) + (A_1 + FA_2)(C + 1) - RT[(2C + 3)(1 + F^2) + F(F - 1)]}{2C + 3} \\
(iii) \quad RT < \frac{A_1}{2}
\]
Comparative Statics
Main Results

**Proposition**

\[ \frac{\partial x_1^{PC}}{\partial T} > 0, \frac{\partial x_2^{PC}}{\partial T} < 0, \left| \frac{\partial x_1^{PC}}{\partial T} \right| > \left| \frac{\partial x_2^{PC}}{\partial T} \right|, \]
\[ \frac{\partial y_1^{PC}}{\partial T} < 0, \frac{\partial y_2^{PC}}{\partial T} > 0 \text{ if } C < \frac{F - 1}{1 + F^2}, \frac{\partial \mu^{PC}}{\partial T} > 0. \]

**Proposition**

\[ \frac{\partial x_1^{CO}}{\partial T} > 0, \frac{\partial x_2^{CO}}{\partial T} < 0, \left| \frac{\partial x_1^{CO}}{\partial T} \right| > \left| \frac{\partial x_2^{CO}}{\partial T} \right|, \]
\[ \frac{\partial y_1^{CO}}{\partial T} < \frac{\partial y_2^{CO}}{\partial T} < 0, \frac{\partial \mu^{CO}}{\partial T} > 0. \]

**Proposition**

*Off-peak RE generation under CO exceeds that under PC only if*
\[ T < \frac{(A_2 - FA_1)(C+2)C}{R(F-1)(C+3)}. \]
Decomposition
Main Results

Proposition

\[ \frac{\partial x_2^{PC}}{\partial D} > \frac{\partial x_1^{PC}}{\partial D} > 0, \quad \frac{\partial y_2^{PC}}{\partial D} < \frac{\partial y_1^{PC}}{\partial D} < 0, \quad \frac{\partial \mu^{PC}}{\partial D} < 0. \]

Proposition

\[ \frac{\partial x_2^{CO}}{\partial D} > \frac{\partial x_1^{CO}}{\partial D} > 0, \quad \frac{\partial y_2^{CO}}{\partial D} < \frac{\partial y_1^{CO}}{\partial D} < 0, \quad \frac{\partial \mu^{CO}}{\partial D} < 0. \]
Main Results

- Assuming $T = 0$ and any $D \in S_{PC} \cap S_{\mu}^{CO}$

**Proposition**

\[
\frac{\partial x_{1}^{PC}}{\partial F} < 0, \quad \frac{\partial y_{1}^{PC}}{\partial F} > 0, \quad \frac{\partial x_{2}^{PC}}{\partial F} < 0, \quad \frac{\partial y_{2}^{PC}}{\partial F} > 0 \quad \text{if} \quad F < \frac{(D - A_1) + \sqrt{A_2^2 + (D - A_1)^2}}{A_2}
\]

- Proposition

\[
\frac{\partial x_{1}^{CO}}{\partial F} < 0, \quad \frac{\partial x_{2}^{CO}}{\partial F} < 0, \quad \frac{\partial y_{1}^{CO}}{\partial F} > 0, \quad \frac{\partial y_{2}^{CO}}{\partial F} > 0, \quad \frac{\partial \mu^{CO}}{\partial F} > 0.
\]
Numerical Examples
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$T$</td>
<td>20</td>
</tr>
</tbody>
</table>
Marginal Value of RE Storage

\[ \mu^P \]

\[ \mu^C \]

\[ \mu^O \]

\[ T (\$/t) \]

\[ \mu (\$/MWh) \]
Impact of Carbon Policy

RE Production

\[ x^{PC}_j \text{ and } x^{CO}_j \text{ (MWh)} \]

\[ T \text{ ($/t$)} \]
Thermal Production

The graph illustrates the relationship between thermal production ($y_j^T$) and the carbon price ($T$). The production is shown for different scenarios, indicated by different lines:

- $y_1^{PC}$
- $y_2^{PC}$
- $y_1^{CO}$
- $y_2^{CO}$

The y-axis represents the thermal production (MWh), while the x-axis represents the carbon price ($/t$). The graph shows a downward trend as the carbon price increases, indicating a decrease in thermal production.
Impact of Carbon Policy

Producer Profits

- $\Pi_{x}^{PC}$
- $\Pi_{y}^{PC}$
- $\Pi_{x}^{CO}$
- $\Pi_{y}^{CO}$

Introduction
Mathematical Formulation
Comparative Statics
Numerical Examples
Conclusions
Carbon Emissions and Social Welfare

![Graphs showing the relationship between carbon policy and emissions/social welfare.](image-url)
Marginal Value of RE Storage

The graph illustrates the marginal value of RE storage as a function of the demand for energy, denoted by $D$ (MWh). The line $\mu^{PC}$ represents the marginal value with perfect competition, while $\mu^{CO}$ indicates the marginal value in a competitive oligopoly. The graph shows a downward trend, indicating that as the demand for energy increases, the marginal value decreases.
Impact of RE Availability

RE Production

![Graph showing RE production over different values of D (MWh). The graph plots $x_{PC}^j$, $x_{PC}^2$, $x_{CO}^j$, $x_{CO}^1$, and $x_{CO}^2$ against D (MWh).]
Impact of RE Availability

Thermal Production

\[ \begin{align*}
\text{\( y_{j}^{PC} \))} & \quad \text{(MWh)} \\
\text{\( y_{j}^{CO} \))} & \quad \text{(MWh)} \\
\end{align*} \]

\[ D \text{ (MWh)} \]

- \( y_{1}^{PC} \)
- \( y_{2}^{PC} \)
- \( y_{1}^{CO} \)
- \( y_{2}^{CO} \)
Producer Profits

- $\Pi_x^{PC}$
- $\Pi_y^{PC}$
- $\Pi_x^{CO}$
- $\Pi_y^{CO}$

Impact of RE Availability

Profit ($) vs. $D$ (MWh)
Carbon Emissions and Social Welfare

- **Introduction**
- **Mathematical Formulation**
- **Comparative Statics**
- **Numerical Examples**
- **Conclusions**

Impact of RE Availability

![Graph](image)
Impact of RE Storage Efficiency

Marginal Value of RE Storage (PC)
Marginal Value of RE Storage (CO)
RE Production \((T = 0)\)
Impact of RE Storage Efficiency

**RE Production** ($T = 20$)

![Graph showing RE Production](image-url)
Impact of RE Storage Efficiency

Thermal Production \((T = 0)\)
Impact of RE Storage Efficiency

Thermal Production ($T = 20$)
Impact of RE Storage Efficiency

Producer Profits ($T = 0$)
Impact of RE Storage Efficiency

Producer Profits ($T = 20$)
Impact of RE Storage Efficiency

Carbon Emissions and Social Welfare ($T = 20$)
Conclusions
Summary

- Transformation of power sector with higher RE penetration entices more storage operations
  - Examine the impacts of carbon policy, RE availability, and storage efficiency on market equilibria
  - Carbon tax may reverse results from the literature about the role of market power in shifting RE deployment and the marginal value of RE storage
  - With relatively efficient thermal production, carbon taxation may even increase thermal output in peak period under perfect competition
  - More RE availability benefits the RE producer and welfare at the expense of the thermal producer
  - Higher device efficiency is more desirable for society but may be resisted by RE producers
  - A carbon tax aligns private and social incentives more effectively
- Future work: storage investment, transmission constraints, intermittent RE output