Massive Energy Storage Design for Renewable Electricity Generation Systems

Benjamin Omell and Donald J. Chmielewski
Department of Chemical and Biological Engineering, Illinois Institute of Technology, Chicago, IL
Outline

• Introduction and Objectives
• Case Study
• Method: Supervisory Control Scheme and Profit Control
• Case study Results
• Summary and Conclusions
Outline

• Introduction and Objectives
• Case Study
• Method: Supervisory Control Scheme and Profit Control
• Case study Results
• Summary and Conclusions
Power Management With Renewable Energy
Power Management With Renewable Energy

Power Produced \[\text{Equals}\] Power Consumed
Power Management With Renewable Energy

- Wind energy and other renewable sources are not dispatchable.

Power Produced \( \rightarrow \) Equals \( \rightarrow \) Power Consumed

*Graph showing power production and consumption over time.*
Wind Power Generation Comparison with Load Demand

[Graph showing comparison between renewable and load demand over 5 days.]

- **Renewable (MW)**: Variations range from 400 to 700 MW across 5 days.
- **Load (MW)**: Variations range from 1500 to 2500 MW across 5 days.
Wind Power Generation Comparison with Load Demand
Wind Power Generation Comparison with Load Demand

[Graph showing comparison of renewable power generation and load demand over 5 days.]

Renewable (MW) vs. Days

Load (MW) vs. Days
Power Management With Renewable Energy

Renewable + Dispatchable = Load
Power Management With Renewable Energy

Renewable + Dispatchable = Load

MW vs. Days

Illinois Institute of Technology
Department of Chemical and Biological Engineering
Solutions

Power Produced  \[ \text{Equals} \]  Power Consumed

- Wind energy and other renewable sources are not dispatchable
Solutions

Power Produced \quad \text{Equals} \quad \text{Power Consumed}
Forms of Energy Storage

- Large Scale Battery
- Compressed Air
- Flow Batteries
- Flywheel
- Thermal Energy Storage
- Pumped Hydro-storage
Energy Storage Solution

Renewable + Dispatchable = Load
Energy Storage Solution

Renewable

Dispatchable

Load

Energy Storage
Objectives

• Implement supervisory control scheme to regulate power production
• Implement optimization scheme that sizes energy storage device
• Obtain both simultaneously
• Find globally optimal solution
Profit Control

Expected Dynamic Operating Region (EDOR)

Constraints

Backed-off Operating Point (BOP)

Optimal Steady-State Operating Point (OSSOP)
Outline

• Introduction and Objectives
• Case Study
• Method: Supervisory Control Scheme and Profit Control
• Case study Results
• Summary and Conclusions
Forms of Energy Storage

• Large Scale Battery
• Compressed Air
• Flow Batteries
• Flywheel
• Thermal Energy Storage
• Pumped Hydro-storage
Pumped-Hydro Storage

- Pumping water into a high reservoir from a lower one with excess electricity production
- Releasing the water to the lower reservoir and spinning a turbine, during peak demand and low renewable energy production

- Upsides
  - Massive energy storage with minimal cost

- Downsides
  - Economical implementation can be limited by geography
**Examples of Pumped-Storage Hydro in U.S.**

<table>
<thead>
<tr>
<th>Plant</th>
<th>Production Capacity (MW)</th>
<th>Hrs of Available Discharge</th>
<th>GW-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bath County (US, Va)</td>
<td>2700</td>
<td>11</td>
<td>29.7</td>
</tr>
<tr>
<td>Castaic (US,CA)</td>
<td>1566</td>
<td>10</td>
<td>15.66</td>
</tr>
<tr>
<td>Helms (US,CA)</td>
<td>1212</td>
<td>153</td>
<td>185.43</td>
</tr>
<tr>
<td>Northfield MT (US,MA)</td>
<td>1080</td>
<td>10</td>
<td>10.8</td>
</tr>
<tr>
<td>Ludington (US, MI)</td>
<td>1980</td>
<td>9</td>
<td>17.82</td>
</tr>
<tr>
<td>Blenheim-Gilboa (US,NY)</td>
<td>1200</td>
<td>12</td>
<td>14.4</td>
</tr>
<tr>
<td>Lewiston Niagra (US,NY)</td>
<td>2880</td>
<td>20</td>
<td>57.6</td>
</tr>
<tr>
<td>Bad Creek (US,SC)</td>
<td>1065</td>
<td>24</td>
<td>25.56</td>
</tr>
<tr>
<td>Racoon Mt (US,TN)</td>
<td>1900</td>
<td>21</td>
<td>39.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1731.4</strong></td>
<td><strong>30.0</strong></td>
<td><strong>44.1</strong></td>
</tr>
</tbody>
</table>
Outline

• Introduction and Objectives
• Case Study
• **Method: Supervisory Control Scheme and Profit Control**
• Case study Results
• Summary and Conclusions
Control Scheme

\[
\begin{align*}
\dot{P}_C &= r_C \\
\dot{P}_T &= r_T \\
\dot{E}_S &= P_S \\
&= P_C + P_T + P_R - P_L
\end{align*}
\]
Control Scheme

\[
\dot{x} = Ax + Bu + Gw
\]

\[
z = Dx x + Du u
\]

- Disturbance:
  - Power Load \( P_L \)
  - Renewable Power \( P_R \)

- MV:
  - Rate of Coal \( r_T \)
  - Rate of Gas Turbine \( r_c \)

- Outputs:
  - Coal Power \( P_C \) (Performance Var.)
  - Gas Turbine Power \( P_T \) (Performance Var.)
  - Energy Stored \( E_s \) (Performance Var.)
Linear State Model

Controller Prospective

\[
\begin{aligned}
\dot{x} &= Ax + Bu + Gw \\
z &= D_x x + D_u u
\end{aligned}
\]
Profit Control

Constraints

Expected Dynamic Operating Region (EDOR)

Backed-off Operating Point (BOP)

Optimal Steady-State Operating Point (OSSOP)
System Constraints

- Power plants have limits of maximum and minimum production. Long start-up times if shut down
- Plants have limits to rate of changes in power production

<table>
<thead>
<tr>
<th>Coal Power Limitations</th>
<th>Turbine Power Limitations</th>
<th>Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c^{\text{min}} \leq P_c \leq P_c^{\text{max}}$</td>
<td>$P_T^{\text{min}} \leq P_T \leq P_T^{\text{max}}$</td>
<td>$0 \leq E_S \leq E_S^{\text{max}}$</td>
</tr>
<tr>
<td>$P_c^{\text{min}} = 0.8 \cdot P_c^{\text{max}}$</td>
<td>$P_T^{\text{min}} = 0.2 \cdot P_T^{\text{max}}$</td>
<td></td>
</tr>
<tr>
<td>$P_c^{\text{max}} = 1200$</td>
<td>$P_T^{\text{max}} = 1000$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coal Rate Change Limitations</th>
<th>Turbine Rate Change Limitations</th>
<th>Power Production Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_c^{\text{min}} \leq r_c \leq r_c^{\text{max}}$</td>
<td>$r_T^{\text{min}} \leq r_T \leq r_T^{\text{max}}$</td>
<td>$P_S^{\text{min}} \leq P_S \leq P_S^{\text{max}}$</td>
</tr>
<tr>
<td>$r_c^{\text{max}} = 0.05 \cdot P_c^{\text{max}}$</td>
<td>$r_T^{\text{max}} = 6 \cdot P_T^{\text{max}}$</td>
<td></td>
</tr>
</tbody>
</table>
Variable Constraints

Storage Size (MWhr) vs. Days
Variable Constraints
Variable Constraints

Days

Sorage Size (MWhr)

0 5 10 15 20 25 30 35 40
0 2000 4000 6000 8000 10000 12000 14000

Days

Sorage Size (MWhr)
Variable Constraints

![Graph showing variable constraints with storage size (MWhr) on the y-axis and days on the x-axis. The graph includes a red and a black line with horizontal dashed lines indicating constraints.]
Variable Constraints

\[ E_S^{\text{min}} = 0 \]

\[ E_S^{\text{max}} \]

\[ P_S^{\text{max}} \]

\[ P_S^{\text{min}} \]
Disturbance modeling

- A shaping filter is used to model the demand and renewable energy production from the wind generators.

Forcasted Data
Simulated Data
Problem Formulation

\[
\begin{align*}
\min_{X,Y} & \quad \beta_1 E_s^{\max} + \beta_2 P_s^{\max} \\
\xi_i & < \phi_i \Sigma z \phi_i \\
\sigma_i^2 & \leq \xi_i \\
0 & = Ax + Bu + Gw \\
z & = D_x x + D_u u \\
(A + BY) \Sigma x + \Sigma x (A + BY)^T + G \Sigma w G^T & < 0 \\
\begin{bmatrix}
\xi_i \\
(D_x X + D_u Y)^T \phi_i^T
\end{bmatrix} & \leq \begin{bmatrix}
X
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\alpha \sigma_C & < P_C^{\max} - P_C \\
\alpha \sigma_C & < P_C - 0.8 \cdot P_C^{\max} \\
\alpha \sigma_{rC} & < 0.05 \cdot P_C^{\max} - r_C \\
\alpha \sigma_{rC} & < 0.05 \cdot P_C^{\max} + r_C \\
\alpha \sigma_E & < E_S^{\max} - E_S \\
\alpha \sigma_E & < E_S \\
\alpha \sigma_T & < P_T^{\max} - P_T \\
\alpha \sigma_T & < P_T - 0.2 \cdot P_T^{\max} \\
\alpha \sigma_{rT} & < 6 \cdot P_T^{\max} - r_T \\
\alpha \sigma_{rT} & < 6 \cdot P_T^{\max} + r_T \\
\alpha \sigma_S & < P_S^{\max} + P_S \\
\alpha \sigma_S & < P_S^{\max} - P_S
\end{align*}
\]
Problem Formulation

\[
\begin{align*}
\min_{X,Y} & \quad \beta_1 E_s^{\max} + \beta_2 P_s^{\max} \\
\xi_i & < \phi_i \sum \phi_i \\
\sigma_i^2 & \leq \xi_i \\
0 &= Ax + Bu + Gw \\
z &= D_x x + D_u u
\end{align*}
\]
Control Scheme

\[
\begin{align*}
\dot{P}_C &= r_C \\
\dot{P}_T &= r_T \\
\dot{E}_S &= P_S \\
&= P_C + P_T + P_R - P_L
\end{align*}
\]
Problem Formulation

\[
\min_{X,Y} \beta_1 E_s^{\text{max}} + \beta_2 P_s^{\text{max}} \\
\xi_i < \phi_i \sum_z \phi_i \\
\sigma_i^2 \leq \xi_i \\
0 = Ax + Bu + Gw \\
z = D_x x + D_u u \\
\]

\[
(A + BY)\Sigma_x + \Sigma_x (A + BY)^T + G\Sigma_w G^T < 0 \\
\left[ \begin{array}{c} \xi_i \\ \phi_i (D_x X + D_u Y) \\ (D_x X + D_u Y)^T \phi_i^T \\ X \end{array} \right]
\]

\[
\alpha \sigma_C < P_C^{\text{max}} - P_C \\
\alpha \sigma_C < P_C - 0.8 \cdot P_C^{\text{max}} \\
\alpha \sigma_{rC} < 0.05 \cdot P_C^{\text{max}} - r_C \\
\alpha \sigma_{rC} < 0.05 \cdot P_C^{\text{max}} + r_C \\
\alpha \sigma_E < E_S^{\text{max}} - E_S \\
\alpha \sigma_E < E_S \\
\]

\[
\alpha \sigma_T < P_T^{\text{max}} - P_T \\
\alpha \sigma_T < P_T - 0.2 \cdot P_T^{\text{max}} \\
\alpha \sigma_{rT} < 6 \cdot P_T^{\text{max}} - r_T \\
\alpha \sigma_{rT} < 6 \cdot P_T^{\text{max}} + r_T \\
\alpha \sigma_S < P_S^{\text{max}} + P_S \\
\alpha \sigma_S < P_S^{\text{max}} - P_S \\
\]
Problem Formulation

\[
\begin{align*}
\min_{X,Y} & \quad \beta_1 E_s^{\max} + \beta_2 P_s^{\max} \\
\xi_i & < \phi_i \Sigma \phi_i \\
\sigma_i^2 & \leq \xi_i \\
0 & = Ax + Bu + Gw \\
z & = D_x x + D_u u
\end{align*}
\]

\[
(A + BY)\Sigma_x + \Sigma_x (A + BY)^T + G\Sigma_w G^T < 0
\]

\[
\left[
\begin{array}{c}
\xi_i \\
\phi_i (D_x X + D_u Y) \\
(D_x X + D_u Y)^T \phi_i^T
\end{array}
\right] X
\]

\[
\begin{align*}
\alpha \sigma_C & < P_C^{\max} - P_C \\
\alpha \sigma_C & < P_C - 0.8 \cdot P_C^{\max} \\
\alpha \sigma_{rC} & < 0.05 \cdot P_C^{\max} - r_C \\
\alpha \sigma_{rC} & < 0.05 \cdot P_C^{\max} + r_C \\
\alpha \sigma_E & < E_S^{\max} - E_S \\
\alpha \sigma_E & < E_S
\end{align*}
\]

\[
\begin{align*}
\alpha \sigma_T & < P_T^{\max} - P_T \\
\alpha \sigma_T & < P_T - 0.2 \cdot P_T^{\max} \\
\alpha \sigma_{rT} & < 6 \cdot P_T^{\max} - r_T \\
\alpha \sigma_{rT} & < 6 \cdot P_T^{\max} + r_T \\
\alpha \sigma_S & < P_S^{\max} + P_S \\
\alpha \sigma_S & < P_S^{\max} - P_S
\end{align*}
\]
Problem Formulation

\[
\min_{X,Y} \beta_1 E_s^{\text{max}} + \beta_2 P_s^{\text{max}}
\]

\[
\xi_i < \phi_i \Sigma \phi_i
\]

\[
\sigma_i^2 \leq \xi_i
\]

\[
0 = Ax + Bu + Gw
\]

\[
z = D_x x + D_u u
\]

\[
(A + BY) \Sigma_x + \Sigma_x (A + BY)^T + G \Sigma w G^T < 0
\]

\[
\begin{bmatrix}
\xi_i \\
\phi_i (D_x X + D_u Y) \\
(D_x X + D_u Y)^T \phi_i^T
\end{bmatrix}
\]

\[
\begin{align*}
\alpha \sigma_C &< P_C^{\text{max}} - P_C \\
\alpha \sigma_C &< P_C - 0.8 \cdot P_C^{\text{max}} \\
\alpha \sigma_{rC} &< 0.05 \cdot P_C^{\text{max}} - r_C \\
\alpha \sigma_{rC} &< 0.05 \cdot P_C^{\text{max}} + r_C \\
\alpha \sigma_E &< E_S^{\text{max}} - E_S \\
\alpha \sigma_E &< E_S
\end{align*}
\]
Reverse-Convex Constraints

- Global solution obtained using branch and bound scheme
Problem Formulation

\[
\min_{X,Y} \beta_1 E_s^\text{max} + \beta_2 P_s^\text{max} \\
(\begin{bmatrix}
\xi_i \\
\phi_i \\
\xi_i^2 \\
0 \\
z = D_x x + D_u u
\end{bmatrix}
\begin{bmatrix}
\alpha \sigma_C < P_C^\text{max} - P_C \\
\alpha \sigma_C < P_C - 0.8 \cdot P_C^\text{max} \\
\alpha \sigma_{rC} < 0.05 \cdot P_C^\text{max} - r_C \\
\alpha \sigma_{rC} < 0.05 \cdot P_C^\text{max} + r_C \\
\alpha \sigma_E < E_s^\text{max} - E_S \\
\alpha \sigma_E < E_S
\end{bmatrix}
\begin{bmatrix}
\phi_i (D_x X + D_u Y) \\
(D_x X + D_u Y)^T \phi_i^T \\
X
\end{bmatrix}
\leq 0
\]

\[
(A + BY) \Sigma_x + \Sigma_x (A + BY)^T + G \Sigma_w G^T < 0
\]
Outline

• Introduction
• Case Study
• Method: Supervisory Control Scheme and Profit Control
• Results
• Summary and Conclusions
Cases

- Case 1: 40% Coal, 40% Gas Turbine, 20% Renewable
- Case 2: 10% Coal, 40% Gas Turbine, 50% Renewable
- Case 3: 75% Coal, 5% Gas Turbine, 20% Renewable

Power Storage Cost ($\beta_1$) $55$/kWh
Power Rating Cost ($\beta_2$) $1300$/kW
Case 1

Dispatchable Power

Days

MW

Coal (MW/hr)

Gas Turbine (MW/hr)

Dispatchable Power Rates

Days

MW

Coal (MW/hr)

Days

Gas Turbine (MW/hr)
Results Case 1

**Gas Turbine**

**Coal**

- Rate (MW/hr) vs. Power (MW) graphs for Gas Turbine and Coal are shown.

- The Gas Turbine graph is a straight line at zero rate for the given power range.

- The Coal graph is an ellipse indicating a more complex relationship.

- The plots demonstrate the efficiency and output characteristics of each fuel type during the specified range of rates and power levels.
Storage Result

**Storage Power**

Days

0 20 40 60 80 100 120 140 160

MW

-2000 -1000 0 1000 2000

**Storage Size**

Days

0 20 40 60 80 100 120 140 160

GWhr

0 5 10 15 20

Days
Results Case 1

**Gas Turbine**

**Coal**

**Storage**
Cases

• Case 1: 40% Coal, 40% Gas Turbine, 20% Renewable
• Case 2: 10% Coal, 40% Gas Turbine, 50% Renewable
• Case 3: 75% Coal, 5% Gas Turbine, 20% Renewable

Power Storage Cost ($\beta_1$) $55/kWh
Power Rating Cost ($\beta_2$) $1300/kW
Results Case 2

Gas Turbine

Coal

Storage

Rate (MW/hr)

Power (MW)

Energy (MWh)

Illinois Institute of Technology
Department of Chemical and Biological Engineering
Cases

- Case 1: 40% Coal, 40% Gas Turbine, 20% Renewable
- Case 2: 10% Coal, 40% Gas Turbine, 50% Renewable
- **Case 3:** 75% Coal, 5% Gas Turbine, 20% Renewable

Power Storage Cost ($\beta_1$) $55 /\text{kWh}$
Power Rating Cost ($\beta_2$) $1300 /\text{kW}$
Results Case 3

Gas Turbine

Coal

Storage
# Results Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>Coal Power</th>
<th>Gas Turbine</th>
<th>Renewable</th>
<th>Storage Size</th>
<th>Storage Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40%</td>
<td>40%</td>
<td>20%</td>
<td>12.9 GWh</td>
<td>948 MW</td>
</tr>
<tr>
<td>2</td>
<td>10%</td>
<td>40%</td>
<td>50%</td>
<td>26.8 GWh</td>
<td>1398 MW</td>
</tr>
<tr>
<td>3</td>
<td>75%</td>
<td>5%</td>
<td>20%</td>
<td>61.1 GWh</td>
<td>1188 MW</td>
</tr>
</tbody>
</table>
Economic Coefficients Sensitivity

\[ \min_{X,Y} \beta_1 E_s^{\text{max}} + \beta_2 P_s^{\text{max}} \]

- The capital cost range for energy storage 5-100 $/kWh
- The capital cost range for power rating 600-2000 $/kW

Power rating cost can range from 6 times to 400 times the cost of the energy storage

<table>
<thead>
<tr>
<th>Power Rating Cost $/kW</th>
<th>Storage Cost $/kWh</th>
<th>Storage MWh</th>
<th>Power MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,300</td>
<td>$100</td>
<td>12,674</td>
<td>956</td>
</tr>
<tr>
<td>$1,300</td>
<td>$55</td>
<td>12,884</td>
<td>948</td>
</tr>
<tr>
<td>$1,300</td>
<td>$26</td>
<td>13,549</td>
<td>932</td>
</tr>
<tr>
<td>$1,300</td>
<td>$13</td>
<td>15,638</td>
<td>905</td>
</tr>
</tbody>
</table>
Conclusions

Conclusion
• Presented methodology that regulates power production with a optimal controller
• Developed optimization scheme that designs power storage facilities
• Solved both problems simultaneously and arrived at a global optimal solution
• Sensitivity to cost parameters is small

Acknowledgements
• Department of Chemical and Biological Engineering, IIT
• NSF-CBET-0967906