Optimal Design of Hybrid Energy System with PV/ Wind Turbine/ Storage: A Case Study

Presenter: Amit Kumar Tamang
PhD Student

Supervisor: Prof. Weihua Zhaung

Smart Grid Research Group at BBCR

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Outline

• Introduction
• System Model
• Admissible Design [HOMER simulation]
• Optimal Design
• Discussion and Conclusion
1. Introduction

- Remote area power networks: Diesel engine and high cost (fuel transportation, environmental)
- Replacing diesel generation with renewable generation supplemented with batteries and use diesel engine as back up.
- Case study of Santa Catalina Island in California (electricity generated by diesel and transported by ship from the mainland, peak demand 5.3 MW in 2008)
1. Introduction: Objective

- To determine the size of energy resources (PV, wind turbine, batteries) that assures a maximum risk level of supply and demand mismatch.
- Then choose a minimum-cost design among all the designs satisfying given maximum risk level.
2. System Model

• Model of a hybrid energy system consists of PV arrays, wind turbines and battery storages – using them to define admissible design

• Using empirical whether data in HOMER simulator to compute admissible designs

[alternatively analytic model can be built to compute admissible designs]
2. System Model: load-shedding model

- b(t): The amount of energy stored at battery at time t or state of charge of battery.
- s(t): The amount of energy generated by PV array of 1 kW at time t.
- w(t): The amount of energy generated by Wind turbine of 1 kW at time t.
- d(t): the amount of demand at time t.

Fig. 1: The hybrid energy system for Catalina Island.

Total generation by renewable resources:

\[ g(t) := \gamma_1 s(t) + \gamma_2 w(t) \]

\[ \gamma_1 \] # of PV array
\[ \gamma_2 \] # of Wind Turbine

**Load shedding event:** When \( d(t) > g(t) + b(t) \)
2. System Model: Battery Model

**Simple deterministic battery model:**

\[
b(t + 1) = b(t) + f(b(t), g(t) - d(t); b, \overline{b})
\]

\[
f(b(t), g(t) - d(t); b, \overline{b}) \geq 0 \quad \text{for} \quad g(t) > d(t)
\]

\[
f(b(t), g(t) - d(t); b, \overline{b}) \leq 0. \quad \text{for} \quad g(t) < d(t)
\]

\[
b(t + 1) = b(t) + \left[ g(t) - d(t) \right]^{r_1(t)}_{r_2(t)},
\]

where \([x]_a^c = \max \{ \min \{ x, c \}, a \} \), \(a < c\), and

- **Charging**\(\ r_1(t) := \alpha_1(\overline{b} - b(t)), \quad \)where \(\alpha_1, \alpha_2 \in (0, 1)\)
- **Discharging**\(\ r_2(t) := \alpha_2(b(t) - \overline{b}), \quad \)

\[
f = \begin{cases} 
\min \{ \epsilon_1(g(t) - d(t)), r_1(t) \}, & \text{if } g(t) \geq d(t) \\
\max \{ \epsilon_2^{-1}(g(t) - d(t)), -r_2(t) \}, & \text{otherwise.} 
\end{cases}
\]

\(\epsilon_1 \in (0, 1)\)\quad \text{Charging Efficiency}
\(\epsilon_2 \in (0, 1)\)\quad \text{Discharging Efficiency}

**Load shedding event:** \(\epsilon_2^{-1}(d(t) - g(t)) > r_2(t) := \alpha_2(b(t) - \overline{b}), \quad \)

i.e. the energy shortfall exceeds the maximum possible discharge rate.
2. System Model: Risk Measures

- **F_t**: fraction of time when a load-shedding event occurs over horizon [1,T]: T=8760 hrs (1 yr)

- **F_e**: fraction of energy not served when a load-shedding event occurs over horizon [1,T]

\[
F_t := \frac{|L|}{T} \quad L := \{ t \mid \text{Load shedding events} \}
\]

\[
F_e := \frac{\sum_{t \in L} d(t) - g(t) - \epsilon_2 \alpha_2 (b(t) - b)}{\sum_t d(t)}
\]

**F_t** and **F_e** depends upon System Size \((\gamma_1, \gamma_2, \bar{b})\)

A design \((\gamma_1, \gamma_2, \bar{b})\) is admissible if \(F_t \leq \epsilon\) or \(F_e \leq \epsilon\) for risk limit \(\epsilon \in [0, 1]\)
2. System Model: Empirical data for solar and wind output

Fig. 2: Hourly solar radiation in one year on Long Beach, CA, USA

Fig. 3: Hourly wind speed in one year on an island off the coast of Santa Barbara, CA, USA.

Fig. 4: Hourly load demand in one year on the Catalina Island, CA, USA.

Peak demand: 5.3 MW
Load demand: 39 MWh/day
3. Admissible Design: HOMER Simulation

✓ Set of admissible designs for given risk level

**Input:**
Hourly solar radiation, Hourly wind speed, and Load data

Built in modules to simulate solar and wind Power output, various battery dynamics.

**Output:**
Risk level Ft and Fe for each design set.
Set of admissible designs for given risk level.

Table 1: Range and type of simulation components

<table>
<thead>
<tr>
<th>Components</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Arrays</td>
<td>0-10,000 kW</td>
</tr>
<tr>
<td>Wind Turbine</td>
<td>0-10,000</td>
</tr>
<tr>
<td>Type</td>
<td>Generic standard 1 kW turbine</td>
</tr>
<tr>
<td>Battery</td>
<td>15, 20 MWh</td>
</tr>
<tr>
<td>Minimum State of Charge</td>
<td>10 %</td>
</tr>
<tr>
<td>Fraction $\alpha_1$</td>
<td>0.8</td>
</tr>
<tr>
<td>Fraction $\alpha_2$</td>
<td>0.8</td>
</tr>
<tr>
<td>Charging Efficiency $\epsilon_1$</td>
<td>90%</td>
</tr>
<tr>
<td>Discharging Efficiency $\epsilon_2$</td>
<td>90%</td>
</tr>
</tbody>
</table>

Fig 5. The Hybrid energy system with for Catalina Island in HOMER.
3. Admissible Design: Simulation Results

- With increase of $\gamma_1$ and $\gamma_2$ -- $F_t$ decreases (Tradeoff relation)
- Trend is better for fixed value of PV -> irregularity and unpredictability of wind speed, compared with solar radiation

Gives set of admissible design.
4. Optimal Design

- Choose minimum-cost design among the set of admissible designs.
- Tradeoff between system size \((\gamma_1, \gamma_2, \bar{b})\) and risk level Ft or Fe.

**Problem Formulation:**

For set of admissible designs w.r.t to

\[
X_t(\epsilon) := \{ (\gamma_1, \gamma_2, \bar{b}) \geq 0 \mid F_t \leq \epsilon \} \\
\min_{\gamma_1, \gamma_2, \bar{b}} C(\gamma_1, \gamma_2, \bar{b}) \\
\text{subject to} \quad (\gamma_1, \gamma_2, \bar{b}) \in X_t(\epsilon).
\]

or

\[
X_e(\epsilon) := \{ (\gamma_1, \gamma_2, \bar{b}) \geq 0 \mid F_e \leq \epsilon \} \\
\min_{\gamma_1, \gamma_2, \bar{b}} C(\gamma_1, \gamma_2, \bar{b}) \\
\text{subject to} \quad (\gamma_1, \gamma_2, \bar{b}) \in X_e(\epsilon).
\]
4. Optimal Design

Cost Model:

\[ C = C_{PV} + C_{WT} + C_{BA} + C_{CONV} \]

\[ C_{PV} = C_{\text{module}} \times \gamma_1 + C_{O&M_1} \times \gamma_1 \times Life, \]

\[ C_{WT} = C_{\text{turbine}} \times \gamma_2 + C_{O&M_2} \times \gamma_2 \times Life, \]

\[ C_{BA} = C_{\text{battery}} \times \bar{b}, \]

\[ C_{CONV} = C_{\text{converter}} \times S_{CONV}. \]

Design Process:

1) Obtain realistic solar radiation and wind speed data representative of the location of the design.
2) Obtain representative load data.
3) Specify the desired risk measure \( F_t \) or \( F_e \) and acceptable risk level \( \epsilon \).
4) Use a realistic simulator, e.g., HOMER, to characterize the feasible set \( X_t(\epsilon) \) or \( X_e(\epsilon) \) based on the weather and load data.
5) Determine the cost function \( C(\gamma_1, \gamma_2, \bar{b}) \).
6) Estimate a solution to the optimization problem for an optimal design \( (\gamma_1^*, \gamma_2^*, \bar{b}^*) \).
4. Optimal Design: Case Study

Focus on sizing PV arrays and wind turbines

Acceptable risk level $\epsilon = 10\%$

Fixed Battery Capacity

$\bar{b} = 15 \text{ MWh}$ and $\bar{b} = 20 \text{ MWh}$

Table 2: Cost Model parameters for Catalina

<table>
<thead>
<tr>
<th>Name</th>
<th>Cost Data</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>$C_{module}$</td>
<td>$2.80 $/W</td>
<td>[10] for utility-scale PV</td>
</tr>
<tr>
<td>$C_{O&amp;M1}$</td>
<td>$15 $/kW-yr</td>
<td>[11]</td>
</tr>
<tr>
<td>$C_{turbine}$</td>
<td>$2,300 $/per turbine</td>
<td>[12] for 1 kW turbine</td>
</tr>
<tr>
<td>$C_{O&amp;M2}$</td>
<td>$20 $/kW-yr</td>
<td>[10]</td>
</tr>
<tr>
<td>$C_{battery}$</td>
<td>$211 $/kWh</td>
<td>[13]</td>
</tr>
<tr>
<td>$C_{converter}$</td>
<td>$0.715 $/W</td>
<td>[13]</td>
</tr>
</tbody>
</table>

Fig 8. The variation trend of the total construction and operation cost with battery capacity of 15 MWh
4: Optimal Design: Results

- Intersection of Risk curve and Cost curve

Figure 9. The optimal solution to the problem: minimize total cost subject to $F_t \leq 0.1$ with $\theta = 15$ MWh

Table 3. Summary of optimal results

<table>
<thead>
<tr>
<th>PV Arrays</th>
<th>Wind Turbine</th>
<th>Battery Capacity (MWh)</th>
<th>$F_t$</th>
<th>$C$ ($)</th>
<th>COE ($/kWh$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,300</td>
<td>4,000</td>
<td>15</td>
<td>10%</td>
<td>30,352,402</td>
<td>0.201</td>
</tr>
<tr>
<td>PV Arrays</td>
<td>Wind Turbine</td>
<td>Battery Capacity (MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,930</td>
<td>3,000</td>
<td>20</td>
<td>10%</td>
<td>27,778,348</td>
<td>0.185</td>
</tr>
<tr>
<td>PV Arrays</td>
<td>Wind Turbine</td>
<td>Battery Capacity (MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,650</td>
<td>3,000</td>
<td>15</td>
<td>10%</td>
<td>25,891,174</td>
<td>0.177</td>
</tr>
<tr>
<td>PV Arrays</td>
<td>Wind Turbine</td>
<td>Battery Capacity (MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,000</td>
<td>3,000</td>
<td>20</td>
<td>10%</td>
<td>25,014,342</td>
<td>0.172</td>
</tr>
</tbody>
</table>

Comparable estimated renewable cost:
Conventional Power cost in U.S. is 9.48 cent/kWh (2009):

COE is less for battery capacity 20 MWh compared to 15 MWh
Discussion

• No consideration of effect of stochastic weather, load profiles, transmission and distribution of the power network on design results.

• Markov chain model (average behavior but with simple analytical approximations) [1] in contrast to HOMER simulation.

Conclusion

• Tradeoff between the total construction cost and acceptable risk levels has been demonstrated.
• Cost of energy for renewable energy is fairly comparable with conventional generation cost.
Thank you !