OPTIMIZING THE ACQUISITION AND OPERATION OF DISTRIBUTED GENERATION SYSTEMS

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November 10, 2010
Research Question

What is the least cost system design and dispatch to meet the electricity demand of a commercial building?
Outline

- Mixed-Integer Program (MIP)
  - Basic Formulation
  - Solution Intuition

- Numerical Example
  - Optimal Design and Dispatch
  - Cost Analysis

- Conclusions and Extensions
MIP: Assumptions

- One entity is the building owner *and* operator.
- Building’s annual load demand is the same for the lifetime of the acquired system.
- Building demand and fuel cell power are constant over each hour.
- Natural gas–fed fuel cells are acquired at the beginning of the time horizon at a fixed cost.
- Fuel cells can operate however the solution dictates.
- Grid prices are fixed over the time horizon.
MIP: Sets and Parameters

Sets

\( m \in M : \) set of all months in a year

\( t \in T_m : \) set of all hours in month \( m \) \( (T = \bigcup_m T_m) \)

Parameters

\( \tau = \) time increment (hours)

\( d_t = \) expected value of electricity demand in hour \( t \) (kW)

\( c = \) amortized, annual capital cost of each fuel cell ($/fuel cell)

\( k = \) maximum power capacity of each fuel cell (kW)

\( g = \) expected value of price of electricity from the fuel cell ($/kWh)

\( p = \) expected value of price of electricity from the grid ($/kWh)

\( \hat{p} = \) expected value of peak price of electricity from the grid ($/kW/month)
MIP: Capital Cost Parameter

\[ \rho = \text{annual interest rate (fraction)} \]

\[ \lambda = \text{average lifetime of the fuel cell (years)} \]

\[ \kappa = \text{total capital cost ($/fuel cell)} \]

\[ \kappa = 1296.482\kappa^{0.809} \]

\[ c = \frac{\kappa e^\rho \lambda}{\lambda} \]
MIP: Fuel Cell Electricity Price Parameter

0.034 therms per kilowatt-hour

\[ p^g = \text{expected value of price of natural gas ($/therm)} \]

\[ \epsilon = \text{electrical efficiency of the fuel cell (fraction)} \]

\[ g = \frac{0.034p^g}{\epsilon} \]
MIP: Variables and Objective

Variables

\[ A = \text{number of fuel cells acquired (integer)} \]

\[ F_t = \text{power generated by fuel cells in hour } t \text{ (kW)} \]

\[ G_t = \text{power bought from the grid in hour } t \text{ (kW)} \]

\[ \hat{G}_m = \text{peak power bought from the grid in month } m \text{ (kW)} \]

Objective

\[
\min AC = \left[ cA + g \sum_t \tau F_t \right] + \left[ p \sum_t \tau G_t + \hat{p} \sum_m \hat{G}_m \right]
\]

Fuel Cell  \quad Grid
MIP: Constraints

\[
F_t + G_t \geq d_t \quad \forall t \in T \\
\hat{G}_m \geq G_t \quad \forall m \in M, t \in T_m \\
F_t \leq kA \quad \forall t \in T \\
F_t, G_t, \hat{G}_m \geq 0 \quad \forall t \in T, m \in M \\
A \geq 0, \text{ integer}
\]

- (1) Demand must be met by fuel cells and grid
- (2) Peak load is greatest hourly load for the month
- (3) Fuel cells cannot exceed their total capacity
- (4)–(5) Non-negativity and integrality
MIP: When will fuel cells be acquired?

\[ AC = \left[ cA + g \sum_t \tau F_t \right] + \left[ p \sum_t \tau G_t + \hat{p} \sum_m \hat{G}_m \right] \]

\[ \hat{G}_m = \max_{t \in T_m} \{ G_t \} \]
\[ G_t = d_t - F_t \]

Mixed System Cost

\[ 1 \leq A \text{ and } F_t \geq 0 \ \forall t \]

Grid-only System Cost

\[ A = 0 \text{ and } F_t = 0 \ \forall t \]

\[ \left[ p \sum_t \tau d_t + \hat{p} \sum_m \max_{t \in T_m} \{ d_t \} \right] \]
MIP: When will fuel cells be acquired?

- The cost of the mixed system is less than the cost of the grid-only system when

\[
\hat{p} \left[ \sum_{m} \left( \max_{t \in T_m} \{d_t\} - \max_{t \in T_m} \{d_t - F_t\} \right) \right] - (g - p) \left[ \sum_{t} \tau F_t \right] > cA
\]

- Reduced Peak Load Costs
- Added Operational Costs

- Fuel cells will be acquired and operated when the net savings in operational costs are greater than the capital cost.
Numerical Example

- Three-story, 54K sqft office building in Boulder, CO
- Annual electricity demand of 445,421 kWh
- Average hourly load demand of 51 kW
- Based on “typical” year demand
- Electricity demand includes lighting, office equipment, and cooling

Simulated by PhD student Andrew Schmidt, Division of Engineering, in *EnergyPlus.*
Example: Demand Parameters

\[ \tau = 1 \text{ hour} \]

\[ d_t = \text{forecasted hourly demand (kW)} \]
Example: Other Parameters

- Commercial Electricity–Secondary General Service
- Commercial Gas–Small Service

\[ c = \$1,777 \text{ annually per fuel cell} \]
\[ k = 20 \text{ kW} \]
\[ g = \$0.011 \text{ per kWh} \]
\[ p = \$0.005 \text{ per kWh} \]
\[ \hat{p} = \$13.83 \text{ per kW per month} \]

\[
c = \frac{\kappa e^{\rho \lambda}}{\lambda} = \frac{14,625 e^{0.04(15)}}{15} = 1,777
\]
\[
g = \frac{0.034 p^g}{\epsilon} = \frac{0.034(0.131)}{0.42} = 0.011
\]
Example: Initial Feasible Solution

- Grid-only system is always feasible in this model

Annual Cost
$24,213

Levelized Cost
$0.054 per kWh

- Fuel Cell Acquisition
- Fuel Cell Operation
- Grid Hourly Load
- Grid Peak Load

\[ \left[ p \sum_t \tau d_t + \hat{p} \sum_m \max \{d_t\} \right] \]

Peak Load Cost
Example: Optimal Solution

- Optimal system has 6 fuel cells (120 kW total)

Annual Cost
$17,333

Levelized Cost
$0.039 per kWh

\[
[ cA + g \sum_{t} \tau F_t ] + [ p \sum_{t} \tau(G_t) + \hat{p} \sum_{m} \max_{t \in T_m} \{G_t\} ]
\]

Peak Load Cost
Example: Optimal Solution

164 – 120 = 44 kW
Cost Analysis

- Does the acquisition condition from before hold?
  \[
  \hat{p} \left[ \sum_{m} \left( \max_{t \in T_m} \{ d_t \} - \max_{t \in T_m} \{ d_t - F_t \} \right) \right] - (g - p) \left[ \sum_{t} \tau F_t \right] > cA
  \]
  \[
  $19,575.05 - $2,028.55 > $10,662.00
  \]
  \[
  $17,546.50 > $10,662.00
  \]

- The net savings pay off the capital investment in 7–9 years, depending on the discount rate.

- The 6 fuel cell system is cheaper than the grid-only system for capital costs up to $17,546.50, but it does not remain optimal (decrease to 4 fuel cells).
Is it better to utilize the fuel cells more?

Levelized cost from fuel cells decreases from $0.043 per kWh to $0.035 per kWh, but annual cost and levelized cost of system increase.
Basic Model Conclusions

- The optimal system design is driven by the reduction of peak load costs.
- The optimal dispatch strategy is to base-load with the grid in months where peak demand exceeds on-site capacity and meet hourly peaks with the fuel cells.
- This basic model provides a foundation for specifying more realistic system characteristics and determining the effect on the optimal design and dispatch.
Extensions

- Cost Measurement
  - Seasonal / Time-of-Day Pricing and Pricing Structures
  - Net Metering

- Fuel Cell Characteristics
  - Different Capacities, Ramp Rates, and Efficiencies
  - Minimum Turn-down Ratio and Cycling
  - Combined Heat and Power

- Renewable Generation
  - Solar Cells, Wind Turbines, and Batteries

- Stochasticity
  - Demand, Prices, and Generation (Renewable)
Questions?

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