OPTIMIZING THE ACQUISITION AND OPERATION OF DISTRIBUTED GENERATION SYSTEMS

Kris Pruitt, PhD Candidate, USAF

Dr. Alexandra Newman, Division of Economics and Business

Dr. Robert Braun, Division of Engineering

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

$\rho =$ annual interest rate (fraction)

$\lambda =$ average lifetime of the fuel cell (years)

$\kappa =$ total capital cost (\$/fuel cell)

$$\kappa = 1296.482k^{0.809}$$

$$c = \frac{\kappa e^{\rho\lambda}}{\lambda}$$

R.J. Braun. Techno-economic optimal design of SOFC systems for residential micro-combined heat and power applications in the U.S. *ASME Journal of Fuel Cell Science and Technology*, 7, June 2010.

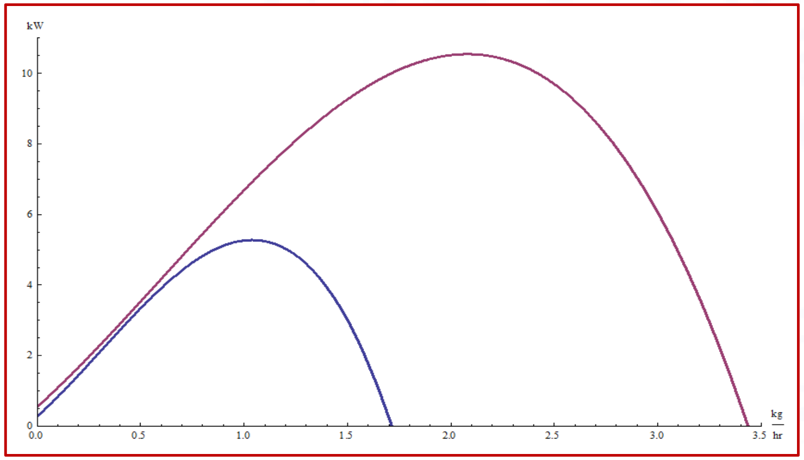
MIP: Fuel Cell Electricity Price Parameter

0.034 therms per kilowatt-hour

$p^g =$ expected value of price of natural gas (\$/therm)

$\epsilon =$ electrical efficiency of the fuel cell (fraction)

$$g = \frac{0.034 p^g}{\epsilon}$$



R.J. Braun. Techno-economic optimal design of SOFC systems for residential micro-combined heat and power applications in the U.S. *ASME Journal of Fuel Cell Science and Technology*, 7, June 2010.

MIP: Variables and Objective

Variables

$A =$ number of fuel cells acquired (integer)

$F_t =$ power generated by fuel cells in hour t (kW)

$G_t =$ power bought from the grid in hour t (kW)

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

Objective

$$\min AC = \underbrace{\left[cA + g\sum_t \tau F_t\right]}_{\textbf{Fuel Cell}} + \underbrace{\left[p\sum_t \tau G_t + \hat{p}\sum_m \hat{G}_m\right]}_{\textbf{Grid}}$$

MIP: Constraints

$$
\begin{aligned}
F_t + G_t &\geq d_t \qquad \forall t \in T && (1)\\
\hat{G}_m &\geq G_t \qquad \forall m \in M, t \in T_m && (2)\\
F_t &\leq kA \qquad \forall t \in T && (3)\\
F_t, G_t, \hat{G}_m &\geq 0 \qquad \forall t \in T, m \in M && (4)\\
A &\geq 0, \quad \text{integer} && (5)
\end{aligned}
$$

- (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?

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

$$\boxed{\begin{aligned} \hat{G}_m &= \max_{t \in T_m}\{G_t\} \\ G_t &= d_t - F_t \end{aligned}}$$

Mixed System Cost

$$\boxed{1 \leq A \text{ and } F_t \geq 0 \ \forall t}$$

$$\left[cA + g\sum_t \tau F_t\right] \quad + \quad \left[p\sum_t \tau(d_t - F_t) + \hat{p}\sum_m \max_{t \in T_m}\{d_t - F_t\}\right]$$

Grid-only System Cost

$$\boxed{A = 0 \text{ and } F_t = 0 \ \forall t}$$

$$\left[p\sum_t \tau d_t + \hat{p}\sum_m \max_{t \in T_m}\{d_t\}\right]$$

MIP: When will fuel cells be acquired?

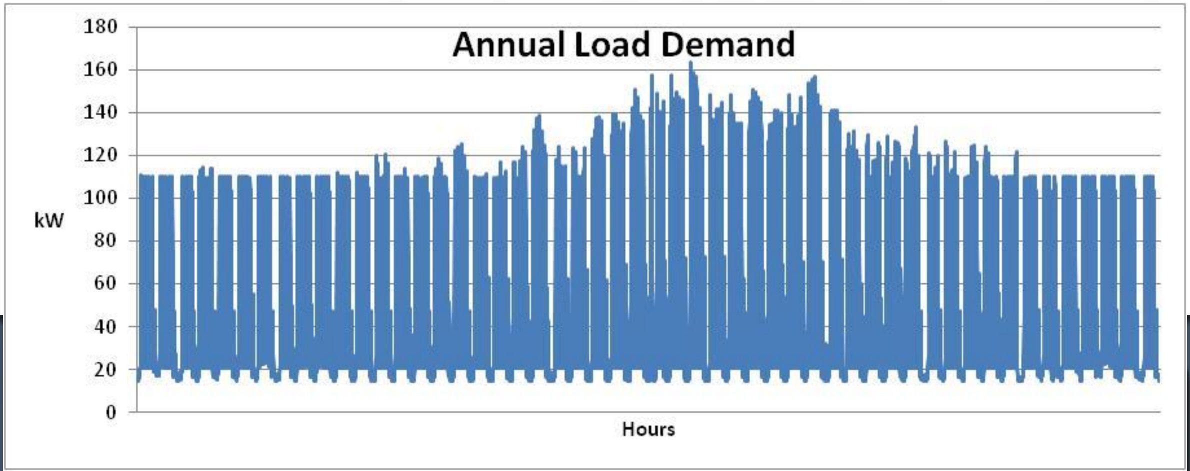
- The cost of the mixed system is less than the cost of the grid-only system when

$$\underbrace{\hat{p}\Big[\sum_m \Big(\max_{t \in T_m}\{d_t\} - \max_{t \in T_m}\{d_t - F_t\}\Big)\Big]}_{\text{Reduced Peak Load Costs}} - \underbrace{(g-p)\Big[\sum_t \tau F_t\Big]}_{\text{Added Operational Costs}} > cA$$

- 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

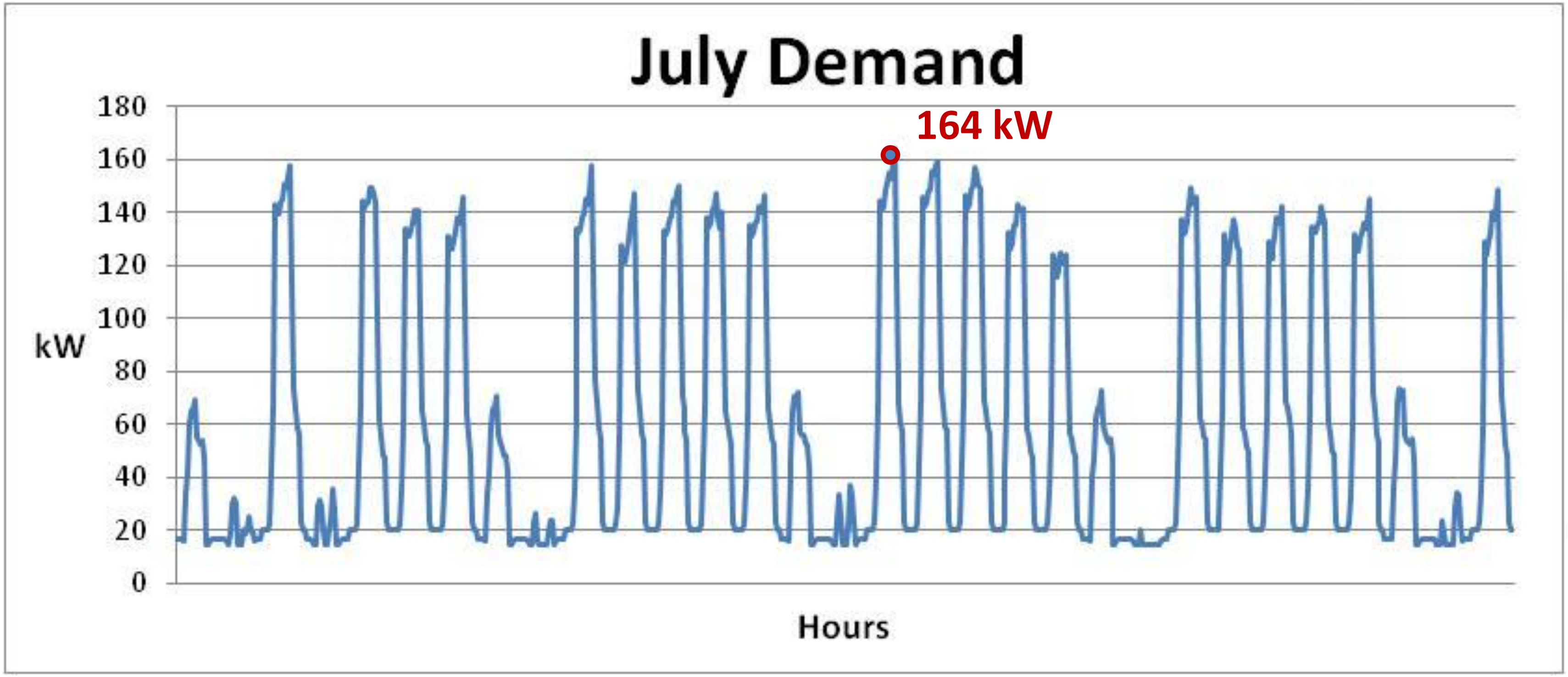


Simulated by PhD student Andrew Schmidt, Division of Engineering, in *EnergyPlus*.

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

$c = \$1,777$ annually per fuel cell

$k = 20$ kW

$g = \$0.011$ per kWh

$p = \$0.005$ per kWh

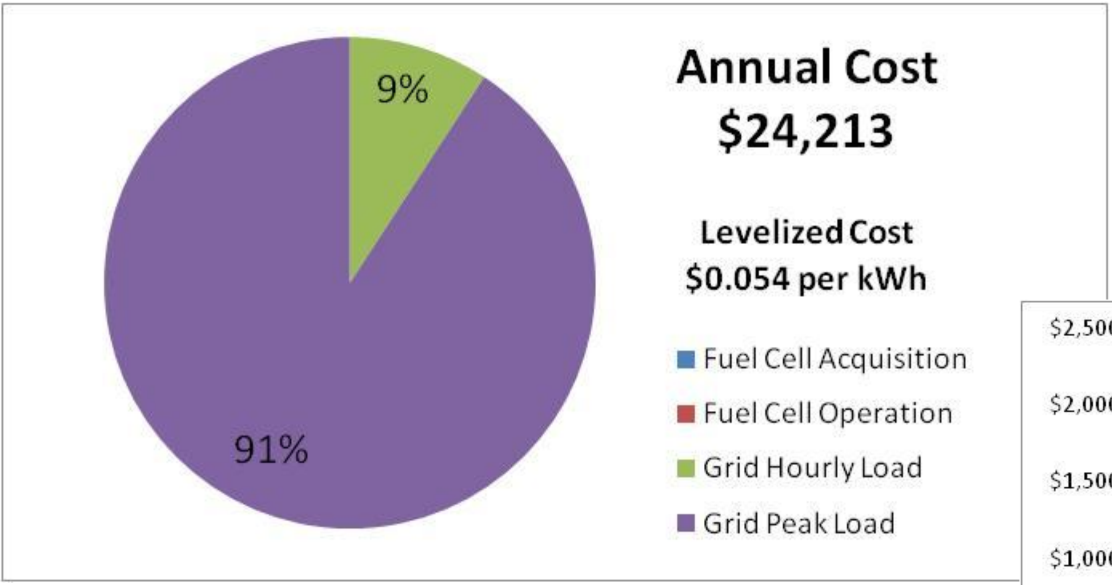
$\hat{p} = \$13.83$ per kW per month

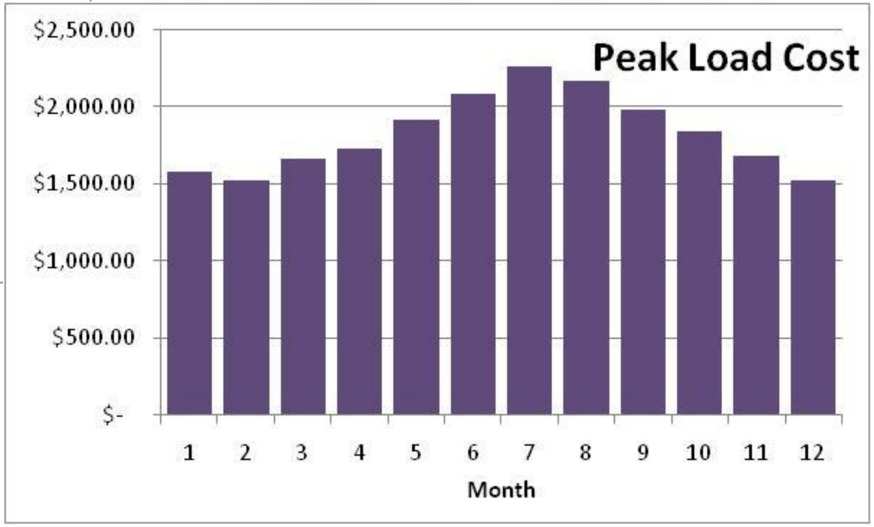
$$
\boxed{
\begin{aligned}
c &= \frac{\kappa e^{\rho\lambda}}{\lambda} = \frac{14,625e^{0.04(15)}}{15} = 1,777 \\
g &= \frac{0.034p^{g}}{\epsilon} = \frac{0.034(0.131)}{0.42} = 0.011
\end{aligned}
}
$$

Xcel Energy. Colorado Rates and Tariff Information. Electric and Gas Tariff Books.
http://www.xcelenergy.com/Colorado/Company/About_Energy_and_Rates

Example: Initial Feasible Solution

- Grid-only system is always feasible in this model

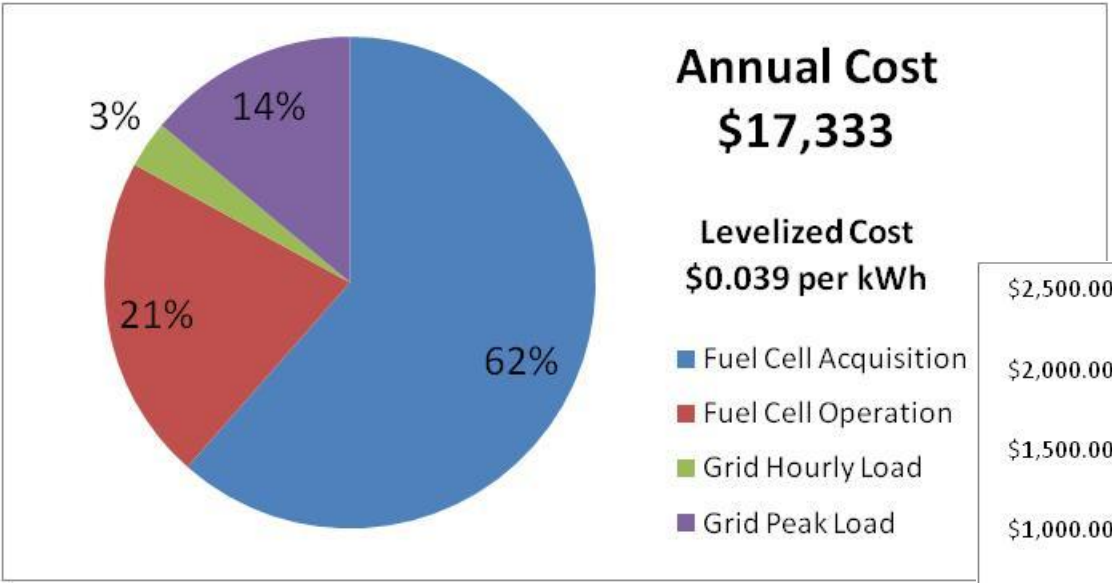


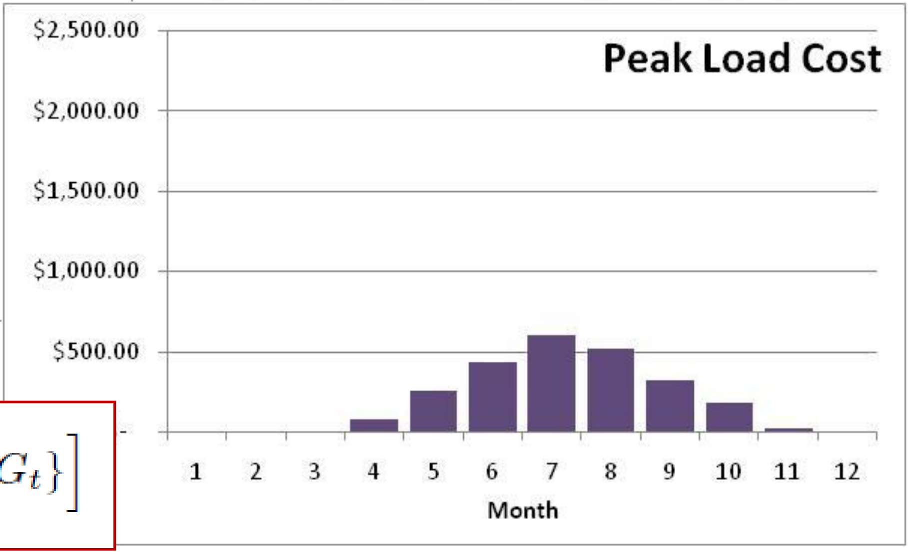


$$\left[p\sum_{t}\tau d_t + \hat{p}\sum_{m}\max_{t\in T_m}\{d_t\}\right]$$

Example: Optimal Solution

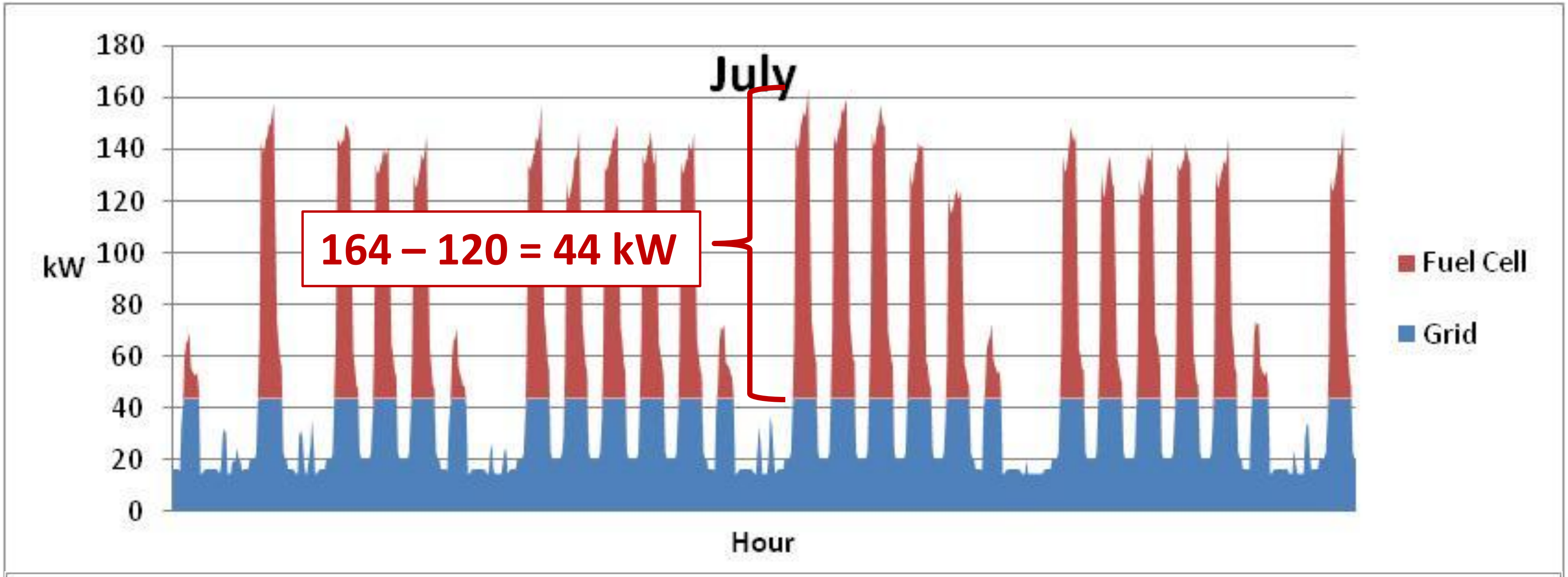
- Optimal system has 6 fuel cells (120 kW total)

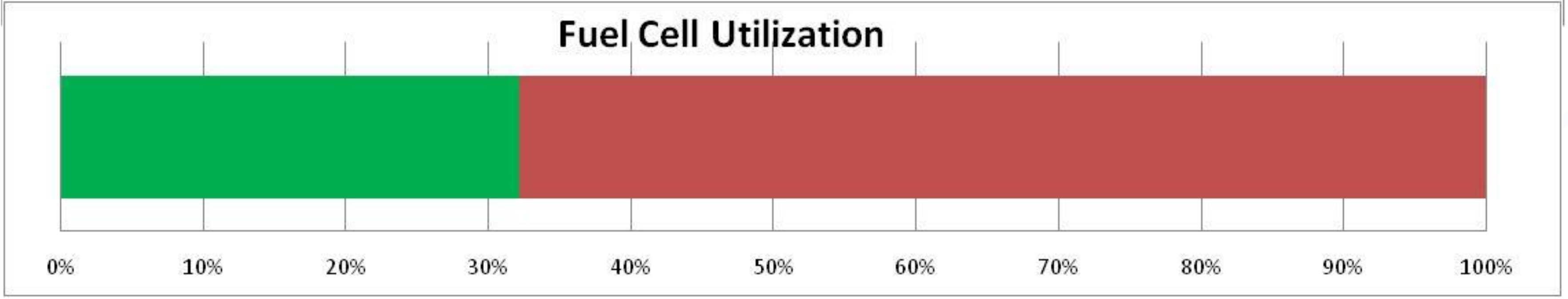




$$\left[cA + g\sum_t \tau F_t\right] + \left[p\sum_t \tau(G_t) + \hat{p}\sum_m \max_{t\in T_m}\{G_t\}\right]$$

Example: Optimal Solution





Cost Analysis

- Does the acquisition condition from before hold?

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

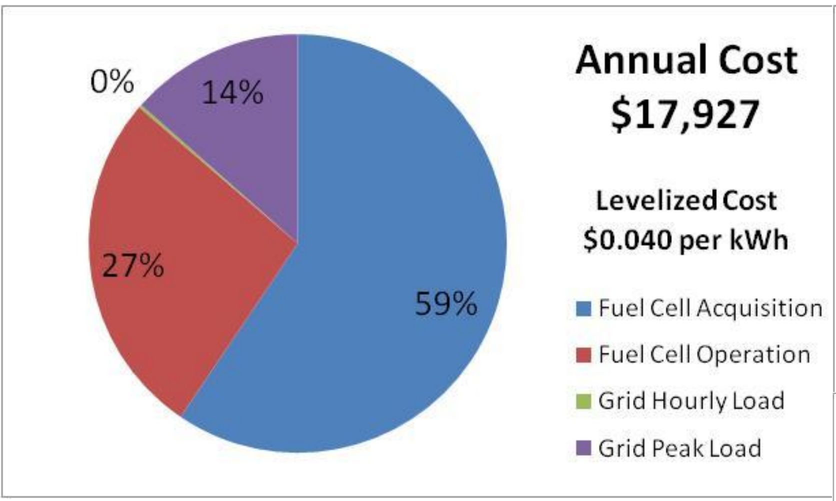
$$\$19,575.05 - \$2,028.55 > \$10,662.00$$

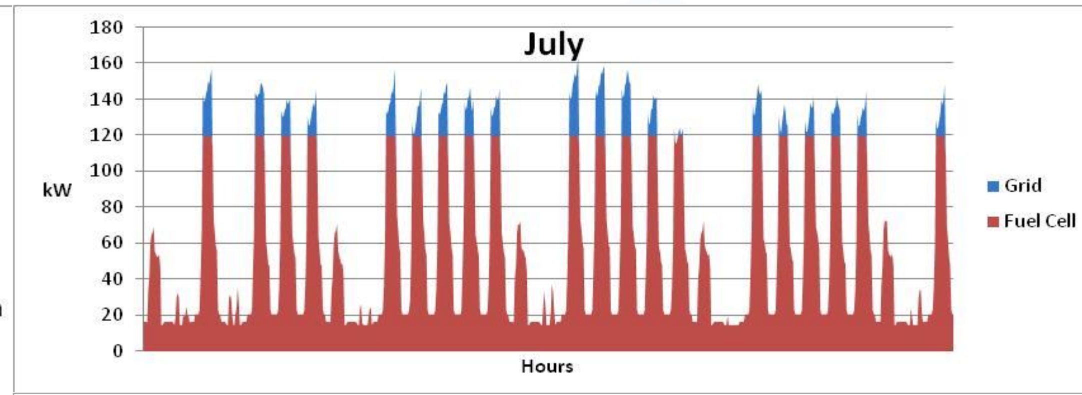
$$\$17,546.50 > \$10,662.00$$

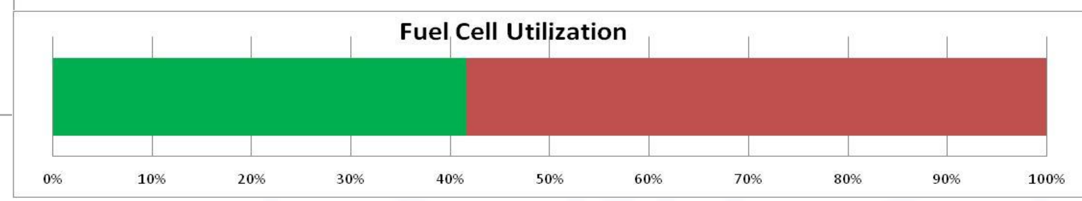
- The net savings pay off the capital investment in 7–9 years, depending on the discount rate.
- The 6 fuel cell system is cheaper than the grid-only system for capital costs up to $17,546.50, but it does not remain optimal (decrease to 4 fuel cells).

Cost Analysis

- 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)

COLORADOSCHOOLOFMINES

Questions?

Kris Pruitt: kpruitt@mines.edu