Optimizing the Acquisition and Operation of On-site Electricity Generation

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Problem Statement

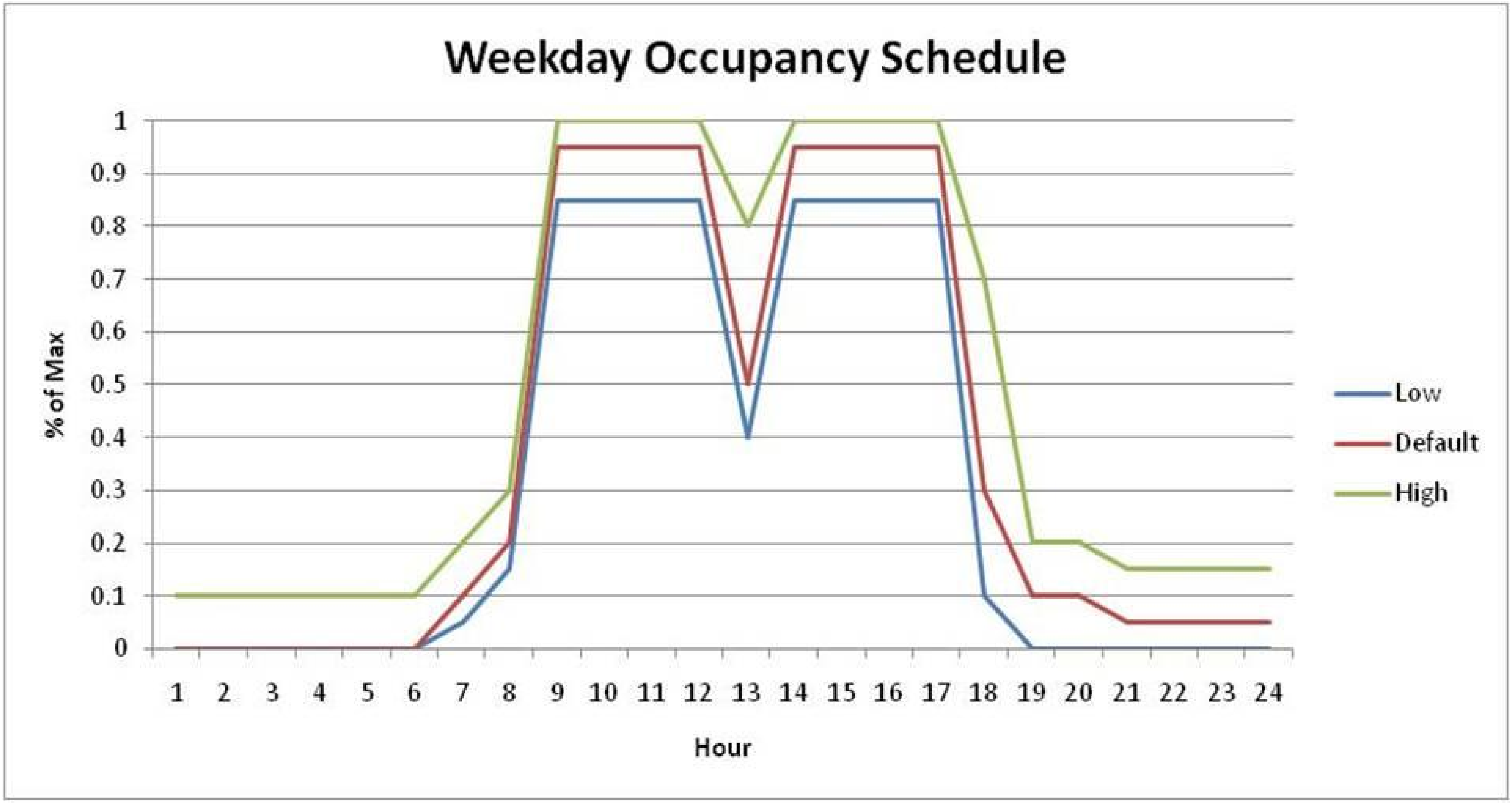
- We have a deterministic, mixed-integer program (MIP) for designing and operating an on-site generation system to supply electricity to a commercial building at minimum cost
- The MIP is constrained by the building's demand, weather, and utility prices which are all uncertain
- What effect does the uncertainty in demand have on the optimal system design and cost?

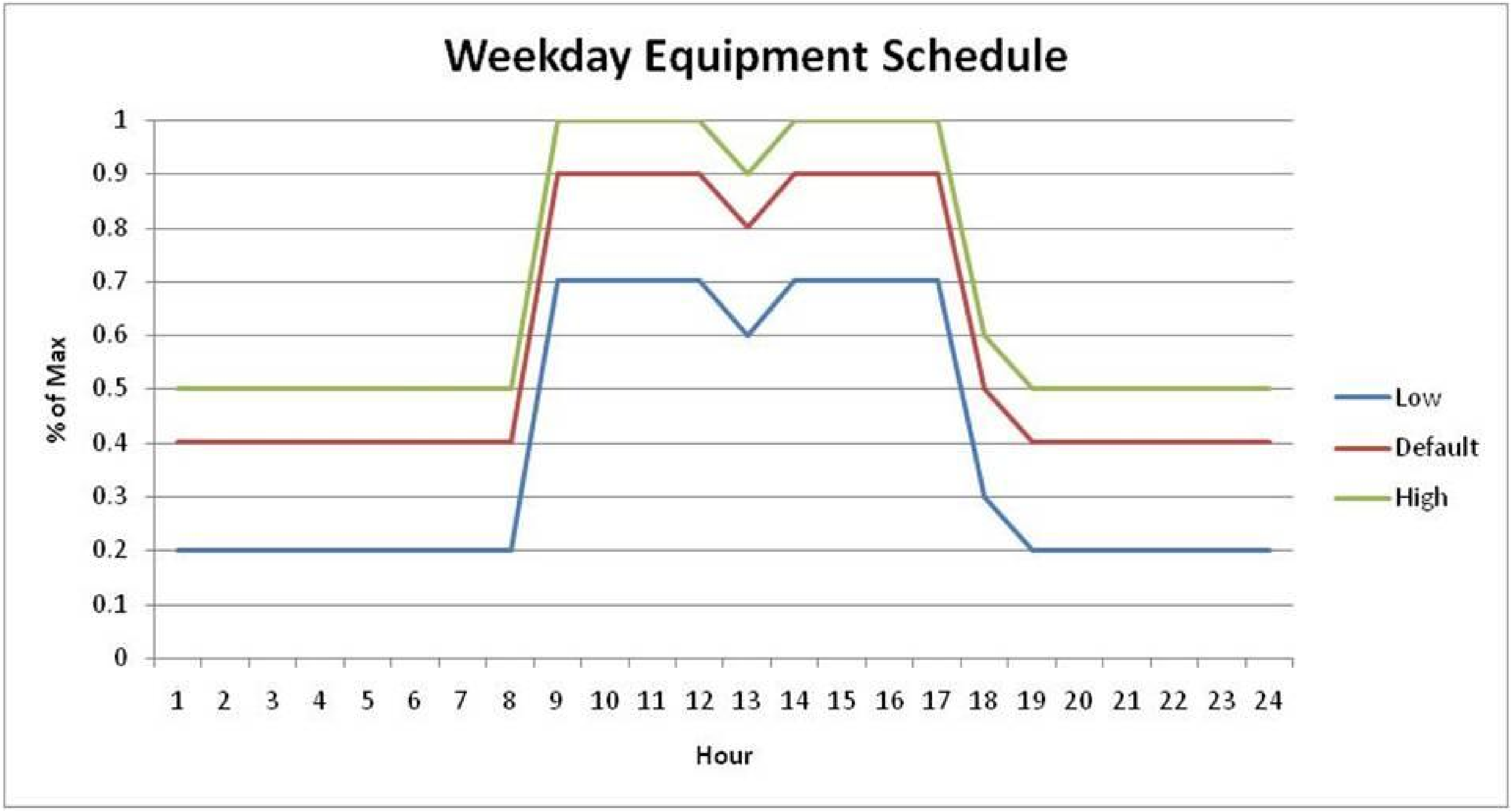
Methodology: Scenario Analysis

- Vary the post-construction determinants of demand in the building simulation (*EnergyPlus*) to produce low, default, and high demand instances
- Solve the MIP with these three demand instances to determine the minimum cost system design for each
- With each system design held fixed, resolve the MIP for each demand instance to determine which design has the lowest *expected* cost

Post-Construction Determinants of Demand

- Based on *EnergyPlus* simulation of three-story, 54K sqft office building in Madison, WI
  - Weather?
  - Occupancy schedule (max = 18 $m^2/person$)
  - Equipment schedule (max = 8.07 $watts/m^2$)
  - Lighting schedule (max = 10.76 $watts/m^2$)


Weekday Occupancy Schedule
% of Max
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Low
Default
High


Weekday Equipment Schedule
% of Max
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
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11
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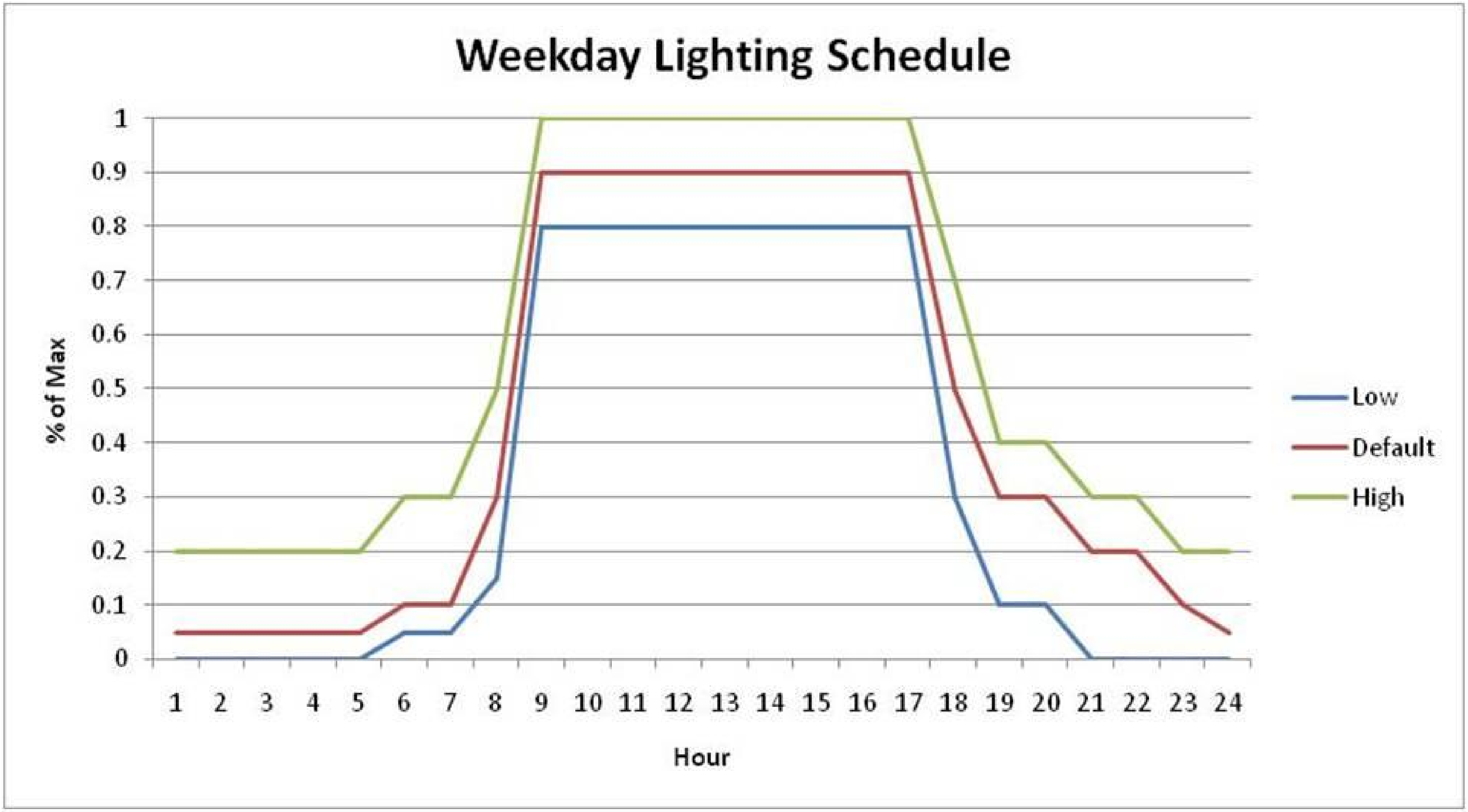
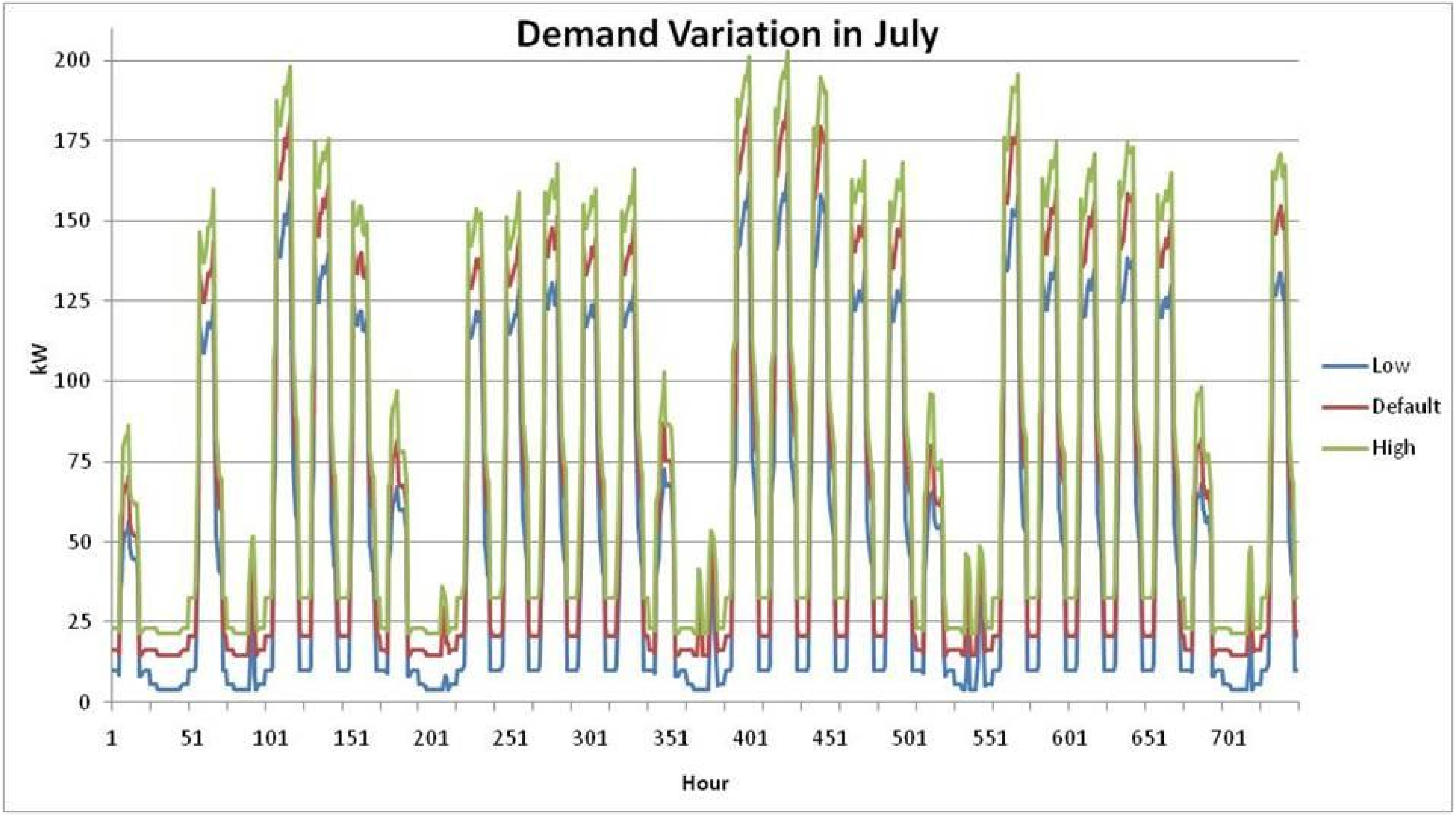
20
21
22
23
24
Hour
Low
Default
High


Weekday Lighting Schedule
% of Max
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Low
Default
High

Demand from setting ALL schedules to low, default, high



Mixed-Integer Program

- Supply hourly electricity demand over the course of one year at minimum design and operation cost

- Can acquire fuel cells, solar cells, and batteries

- Can buy from and sell to the grid

- Based on General Service pricing in Madison, WI

Sets

$g \in G$: set of all elements g that are types of generators

$m \in M_g$: set of all elements m that are models of generator type g

$s \in S$: set of all elements s that are models of batteries

$n \in N$: set of all months n

$t \in T_n$: set of all time periods t in month n ($T = \bigcup_n T_n$)

Demand Parameters

$\tau =$ time increment (hours)

$d_t =$ load demand from building in period t (kW)

Generator Parameters

$f_{gm}^G =$ fixed acquisition cost of generator g, model m (\$/generator)

$v_{gm}^G =$ O&M cost of generator type g, model m (\$/generator)

$c_{gm}^G =$ max power capacity of generator type g, model m (kW)

$\pi_t =$ forecasted percent of solar cell capacity in period t (%)

$\mu_m^G =$ min turn-down ratio of fuel cell model m (%)

$\bar{r}_m =$ max ramp-up rate for fuel cell model m (kW/hr)

$\underline{r}_m =$ max ramp-down rate for fuel cell model m (kW/hr)

$\beta_m =$ slope of fuel equation for fuel cell model m

$\alpha_m =$ intercept of fuel equation for fuel cell model m

Battery Parameters

$f_s^S =$ fixed acquisition cost of battery model s (\$/battery)

$v_s^S =$ O&M cost of battery model s (\$/battery)

$c_s^S =$ max capacity of battery model s (kWh)

$\mu_s^S =$ min state-of-charge of battery model s (%)

$\overline{h}_s =$ max charge rate of battery model s (kW)

$\underline{h}_s =$ max discharge rate of battery model s (kW)

$\overline{\epsilon}_s =$ charge efficiency of battery model s (%)

$\underline{\epsilon}_s =$ discharge efficiency of battery model s (%)

Price Parameters

$\underline{p}^e =$ sale price of electricity to the grid (\$/kWh)

$\bar{p}^e_n =$ customer charge for electricity from the grid in month n (\$)

$\tilde{p}^e =$ energy charge for electricity from the grid (\$/kWh)

$\widehat{p}^e_n =$ peak demand charge for electricity from grid in month n (\$/kW)

$\bar{p}^u_n =$ customer charge for natural gas in month n (\$)

$\tilde{p}^u =$ distribution and supply charge for natural gas (\$/therm)

System Design Variables

$A^G_{gm} =$ 1 if generator type g, model m is acquired, 0 otherwise

$A^S_s =$ 1 if battery model s is acquired, 0 otherwise

System Operation Variables

$F_{mt} =$ 1 if fuel cell model m is turned on in period t, 0 otherwise

$P_{gmt} =$ power from generator g, model m at start of period t (kW)

$I_{st} =$ stock of energy in battery model s at end of period t (kWh)

$\bar{C}_{st} =$ charge rate of battery model s at start of period t (kW)

$\underline{C}_{st} =$ discharge rate of battery model s at start of period t (kW)

$\underline{E}_{gmt} =$ power sold to grid by generator g, model m, period t (kW)

$E_t =$ load supplied by grid in period t (kW)

$\widehat{E}_n =$ maximum load supplied by grid in month n (kW)

Objective

$$\text{Minimize} \sum_{g\in G, m\in M_g} (f_{gm}^G + v_{gm}^G) A_{gm}^G \;+\; \sum_{s\in S} (f_s^S + v_s^S) A_s^S \;+$$

$$\sum_{m\in M_1, t\in T} \tilde{p}^u \tau \left[\alpha_m + \beta_m [(P_{1mt} \;+\; P_{1m,t+1})/2]\right] +$$

$$\sum_{n\in N} \left[\bar{p}_n^u + \bar{p}_n^e\right] + \sum_{n\in N} \widehat{p}_n^e \widehat{E}_n + \sum_{t\in T} \tilde{p}^e \tau E_t \;-\; \sum_{g\in G, m\in M_g, t\in T} \underline{p}^e \tau \underline{E}_{gmt}$$

Demand Constraints

$$
\begin{aligned}
\left[\sum_{m\in M_1}(P_{1mt}+P_{1m,t+1})/2\right] \; + \; \left[\sum_{m\in M_2} P_{2mt}\right] - d_t = & \\
\left[\sum_{g\in G, m\in M_g} \underline{E}_{gmt} - E_t\right] \; + \; \left[\sum_{s\in S}(\bar{C}_{st} - \underline{\epsilon}_s\underline{C}_{st})\right] & \qquad \forall t \in T
\end{aligned}
$$

$$
\begin{array}{rcll}
\underline{E}_{1mt} & \leq & (P_{1mt}+P_{1m,t+1})/2 & \forall m \in M_1, t \in T \\
\underline{E}_{2mt} & \leq & P_{2mt} & \forall m \in M_2, t \in T \\
\widehat{E}_n & \geq & E_t & \forall n \in N, t \in T_n
\end{array}
$$

Fuel Cell Constraints

$$\begin{aligned}
P_{1mt} &\leq c^G_{1m} A^G_{1m} && \forall m \in M_1, t \in T \\
P_{1mt} &\leq c^G_{1m} F_{mt} && \forall m \in M_1, t \in T \\
P_{1mt} &\geq (\mu^G_m c^G_{1m}) F_{mt} && \forall m \in M_1, t \in T \\
A^G_{1m} &\geq F_{mt} && \forall m \in M_1, t \in T \\
P_{1m,t+1} - P_{1mt} &\leq \tau(\bar{r}_m) && \forall m \in M_1, t \in T \ni t < \{T\} \\
P_{1mt} - P_{1m,t+1} &\leq \tau(\underline{r}_m) && \forall m \in M_1, t \in T \ni t < \{T\}
\end{aligned}$$

Solar Cell Constraints

$$P_{2mt} \leq (\pi_t c^G_{2m}) A^G_{2m} \qquad \forall m \in M_2, t \in T$$

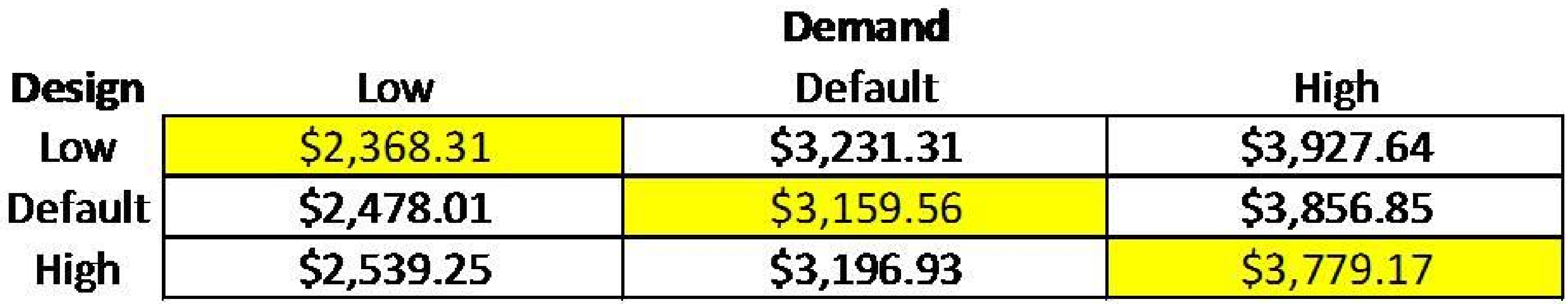
Battery Constraints

$$
\begin{array}{rcll}
I_{st} - I_{s,t-1} & = & \tau\Big[\bar{\epsilon}_s \bar{C}_{st} - \underline{C}_{st}\Big] & \forall s \in S, t \in T \ni t > 1 \\
I_{s1} & = & \tau(\bar{\epsilon}_s \bar{C}_{s1}) & \forall s \in S \\
\underline{C}_{s1} & = & 0 & \forall s \in S \\
I_{st} & \leq & c_s^S A_s^S & \forall s \in S, t \in T \\
I_{st} & \geq & (\mu_s^S c_s^S) A_s^S & \forall s \in S, t \in T \\
\bar{C}_{st} & \leq & \bar{h}_s A_s^S & \forall s \in S, t \in T \\
\underline{C}_{st} & \leq & \underline{h}_s A_s^S & \forall s \in S, t \in T
\end{array}
$$

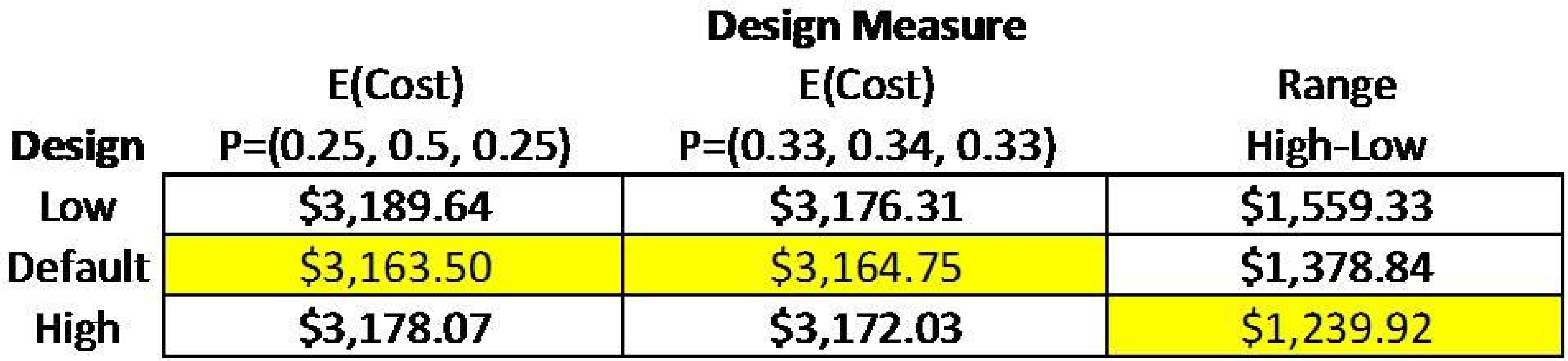
System Design Results for July

- Low Demand System ($d_t = LOW$)
  - 8 x 20kW fuel cells
  - 10 kWh battery
  - $739.48 fixed monthly cost
- Default Demand System ($d_t = DEFAULT$)
  - 9 x 20kW and 1 x 5kW fuel cells
  - $833.55 fixed monthly cost
- High Demand System ($d_t = HIGH$)
  - 10 x 20kW fuel cells
  - $893.80 fixed monthly cost

System Design and Operation Costs (A^G_{gm}, A^S_s fixed)

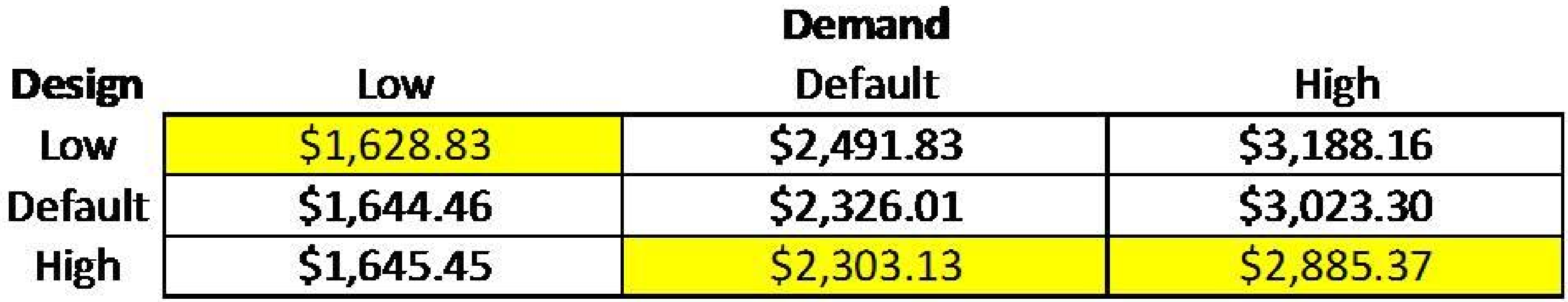


	Demand		
Design	Low	Default	High
Low	$2,368.31	$3,231.31	$3,927.64
Default	$2,478.01	$3,159.56	$3,856.85
High	$2,539.25	$3,196.93	$3,779.17

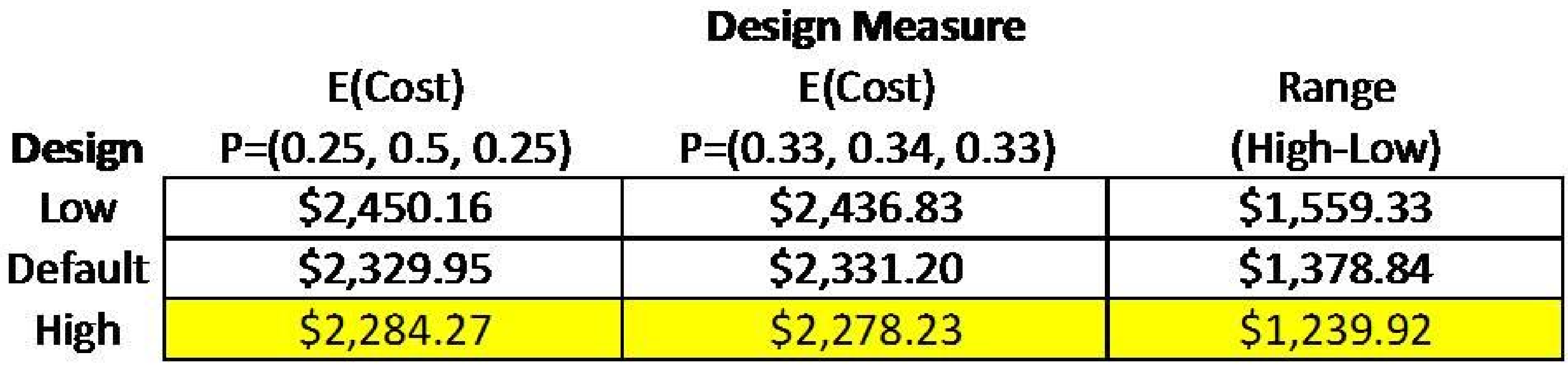


	Design Measure		
	E(Cost)	E(Cost)	Range
Design	P=(0.25, 0.5, 0.25)	P=(0.33, 0.34, 0.33)	High-Low
Low	$3,189.64	$3,176.31	$1,559.33
Default	$3,163.50	$3,164.75	$1,378.84
High	$3,178.07	$3,172.03	$1,239.92

System Operation Costs Only (A^{G}_{gm}, A^{S}_{s} fixed)



		Demand	
Design	Low	Default	High
Low	$1,628.83	$2,491.83	$3,188.16
Default	$1,644.46	$2,326.01	$3,023.30
High	$1,645.45	$2,303.13	$2,885.37



		Design Measure	
Design	E(Cost) P=(0.25, 0.5, 0.25)	E(Cost) P=(0.33, 0.34, 0.33)	Range (High-Low)
Low	$2,450.16	$2,436.83	$1,559.33
Default	$2,329.95	$2,331.20	$1,378.84
High	$2,284.27	$2,278.23	$1,239.92

Conclusions

- A 22% decrease and 18% increase from default demand produces a 31% decrease and 28% increase in operational costs on average across the three system designs
- The High Demand system design has the smallest operational cost fluctuation (29% decrease, 25% increase)
- The High Demand system design has the lowest *expected* operational cost
- The High Demand system differs from the Default Demand system by a single generator (20kW vs. 5kW) and $9,900 total installed capital cost

Future Work

- Perform more detailed cost-benefit analysis between Default and High system designs
- Test demand instances between the low and high
- Perform scenario analysis with weather and pricing
- Develop methodology for selecting the most robust system design