SAND2015-XXXXC
Unclassified Unlimited Release

Exceptional service in the national interest

SAND2015-4669C

Sandia National Laboratories

Optimal Size Tradeoffs between Batteries and Photovoltaics for Expeditionary Energy Operations

Mark A. Smith, Ph.D.[1]
Nadine E. Miner, Ph.D.[2]
Gayle R. Von Eckartsberg[3]
Col. James C. Caley[3]

24 June 2015

1. System Readiness and Sustainment Technologies, Sandia National Laboratories
2. Military and Energy Systems Analysis, Sandia National Laboratories
3. USMC Expeditionary Energy Office (E2O)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

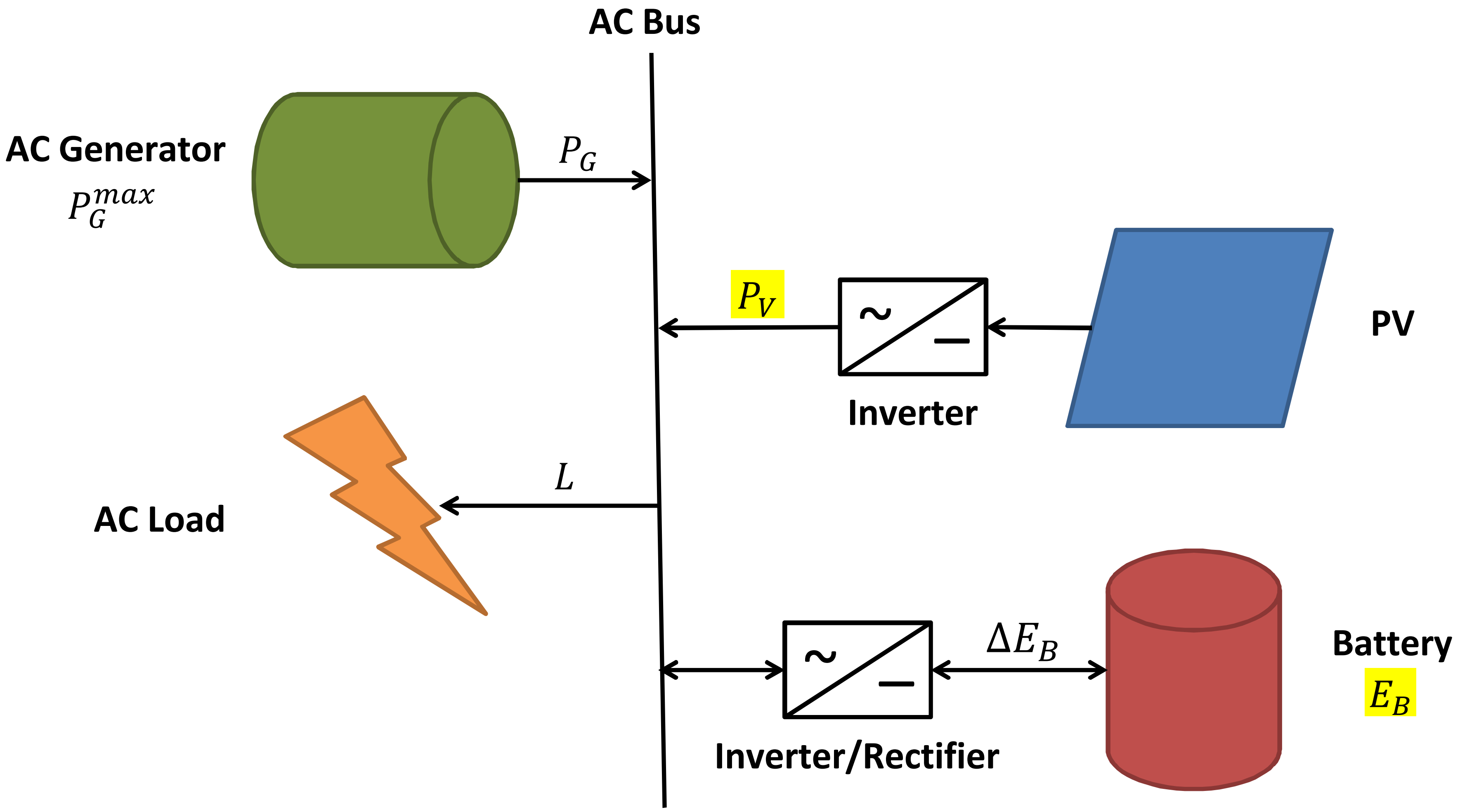
Introduction

- Ground forces require electric power in expeditionary contexts (where, by definition, a power grid is not available)
- Power must come from some combination of fuel-fired generators, renewable energy sources, and batteries
- Problem: Determine optimal combinations of renewables and batteries to add to a network having a given load and generator

Modeling Assumptions

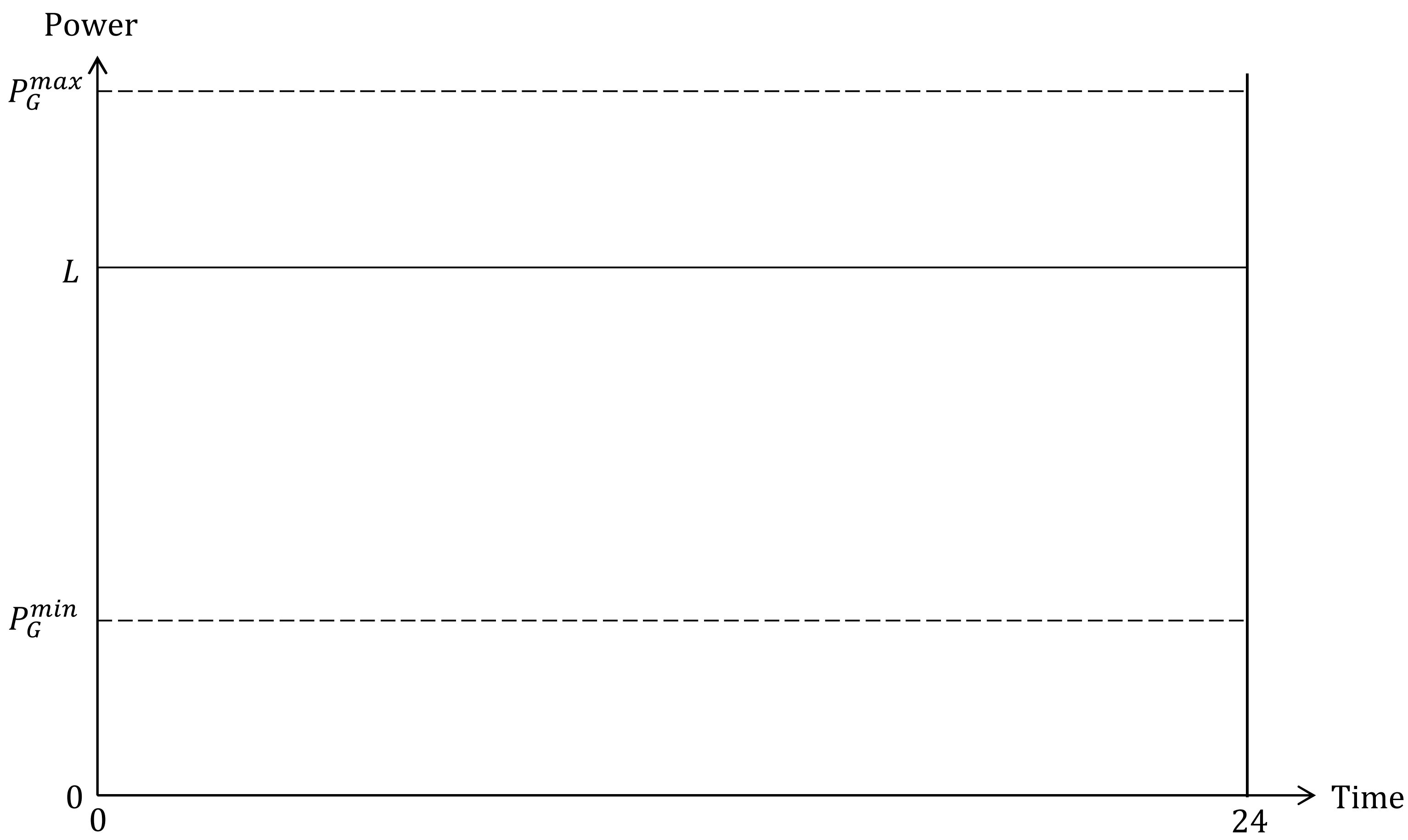
- Many approximations (but they are not bad if made judiciously)
- Abstracting away small details in this way allows derivation of analytic formulas
- Purpose is to develop insights, not exact results (which would require much more detailed data and calculations)

Power Network Model



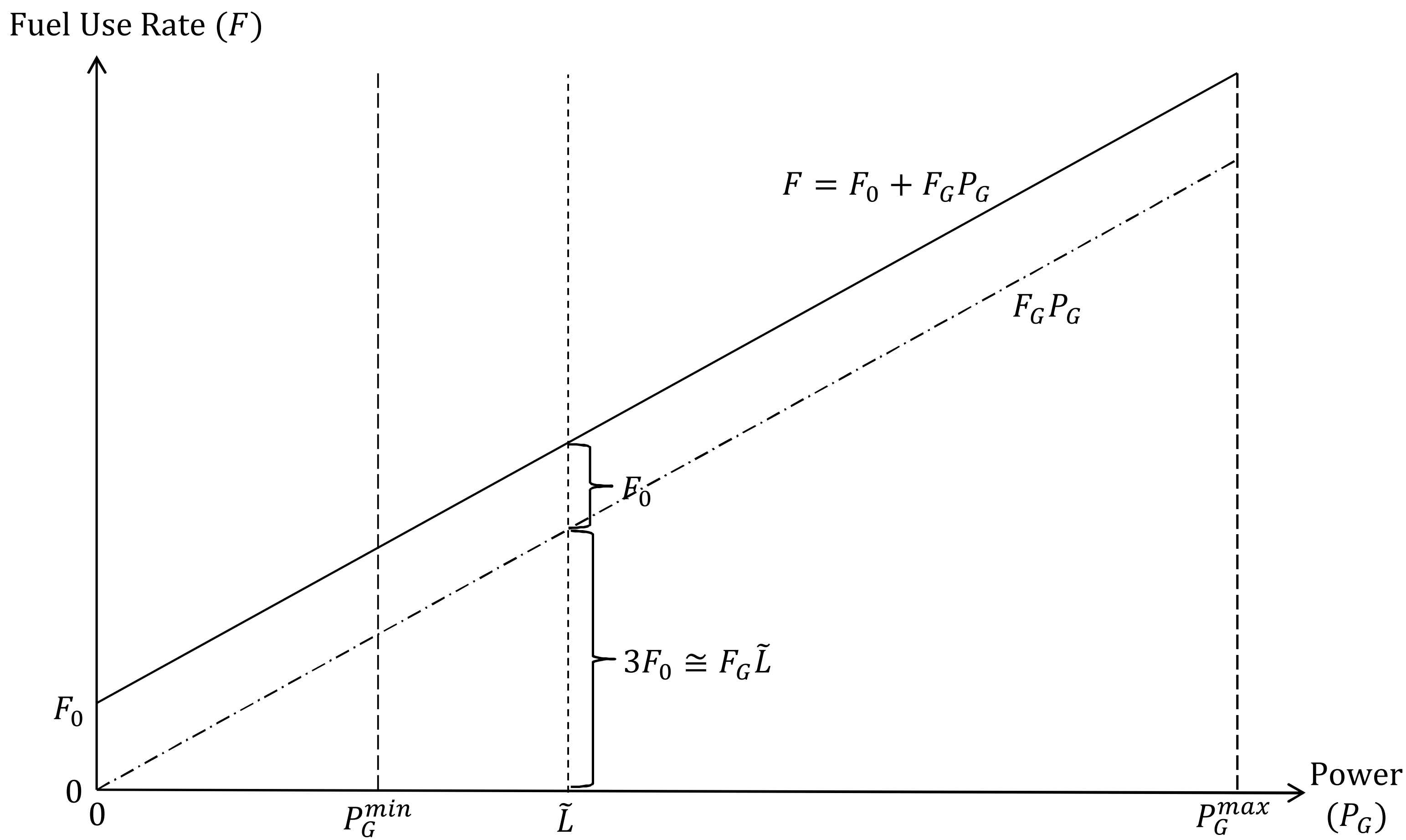
Load Model and Generator Limits

- Constant 24/7
- Example: $L = 25 \text{ kW}, P_G^{max} = 30 \text{ kW}, P_G^{min} = 7.5 \text{ kW}$



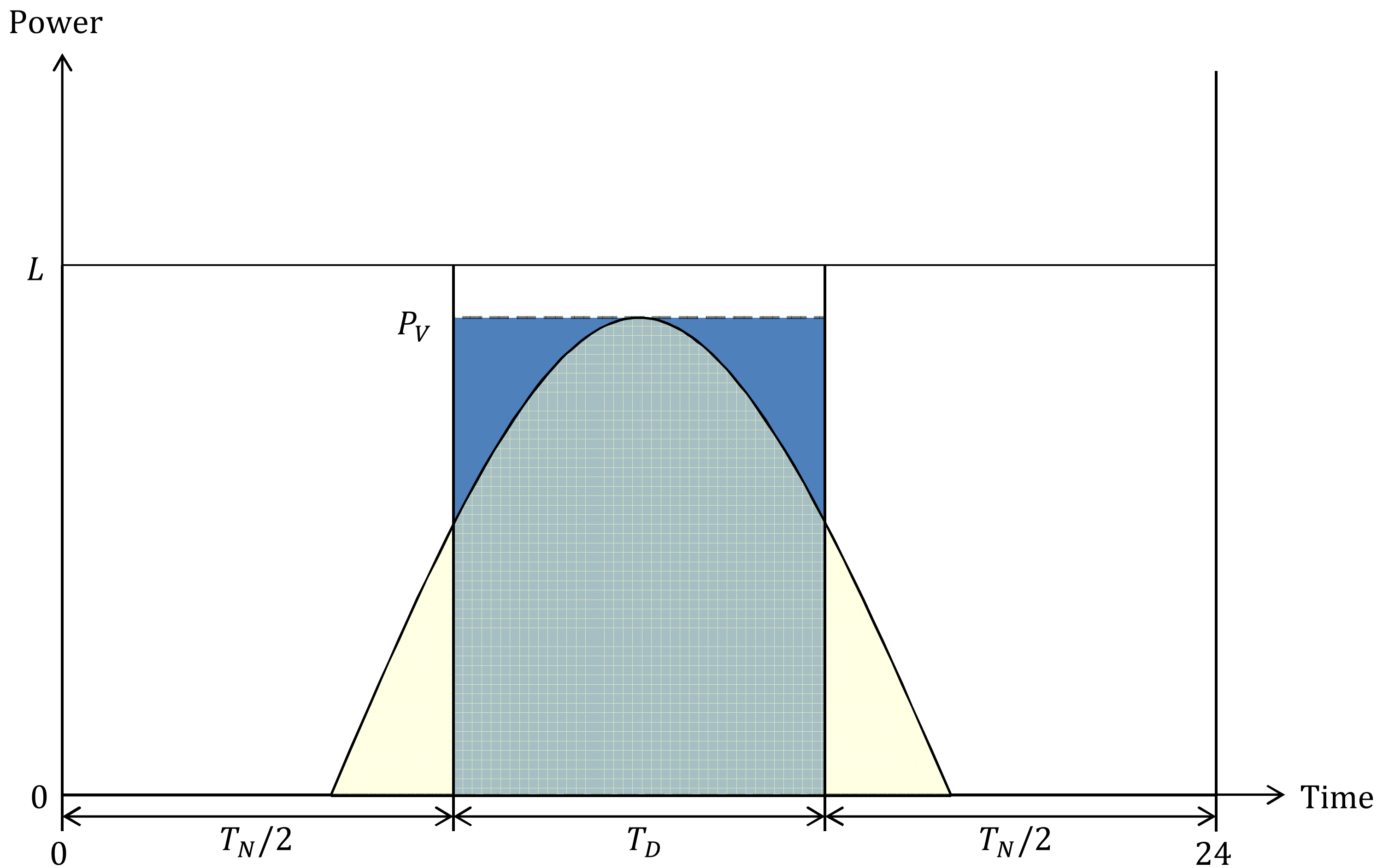
Generator Fuel Use Rate Model

- Linear fuel use per unit time as a function of generator power
  - Intercept (F_0): fuel use rate at zero power output
  - Slope (F_G): fuel use rate per kW of power output



Photovoltaics (PV) Model

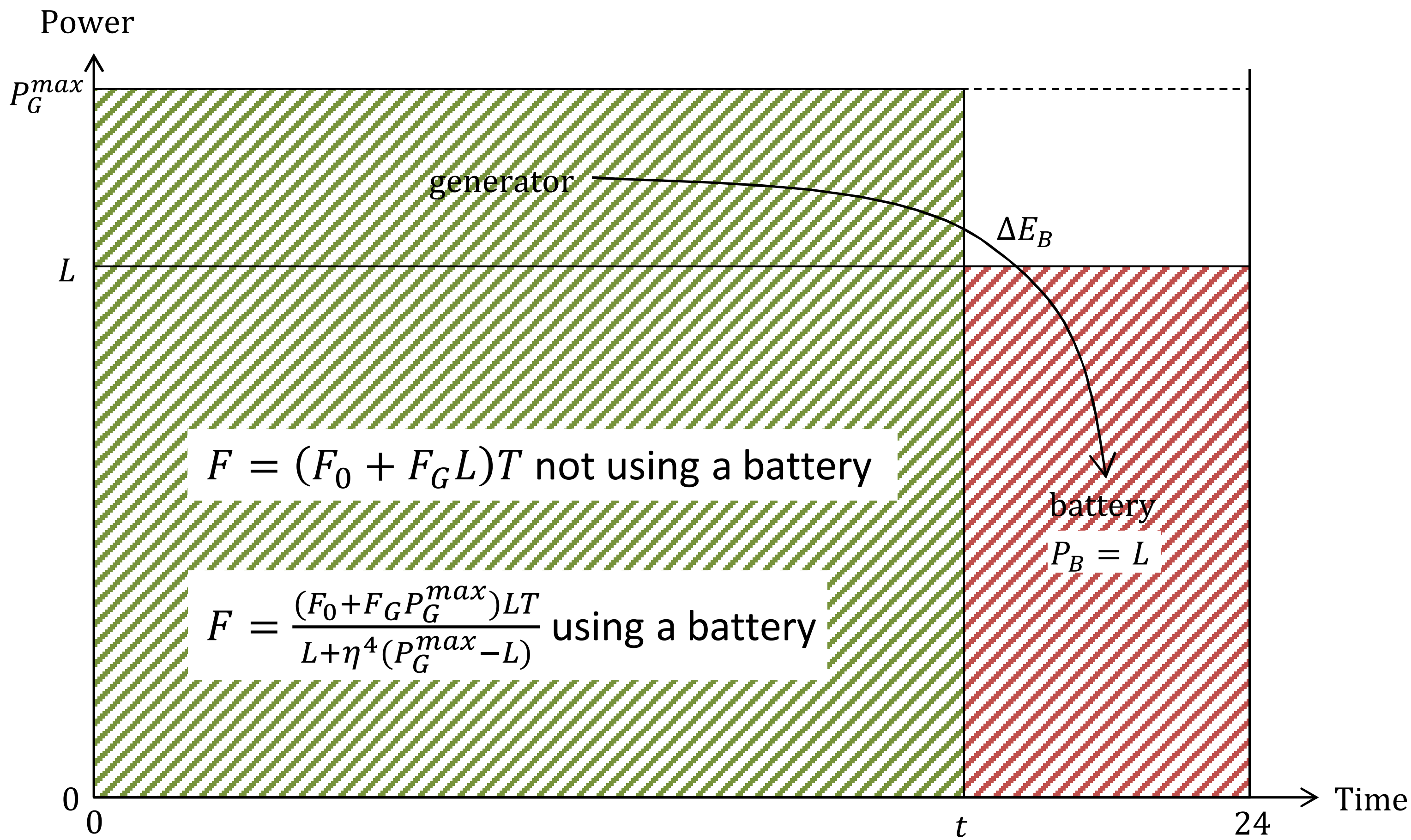
- Rectangular approximation
  - Same maximum (which dictates correct battery use)
  - Same area under the curve (which gives correct total energy output)



Battery Model

- Characterized by a capacity (E_B) which represents the full usable range of energy storage
- No restriction on charging and discharging rates
- Energy conversion losses occur at four stages:
  (1) rectification, (2)charging, (3) discharging, and (4) inversion
- Denote the geometric mean of conversion efficiencies by η (and assume all are equal for simplicity)
- Example: $\eta = 93\%$
- Therefore, the round-trip flow from generator (or PV) to the battery to the load gives an overall efficiency of $\eta^4 = 74.8\% \approx 75\%$ (i.e., 25% loss)

Fuel Use (per day) via Cycle Charging a Battery using just a Generator, no PV

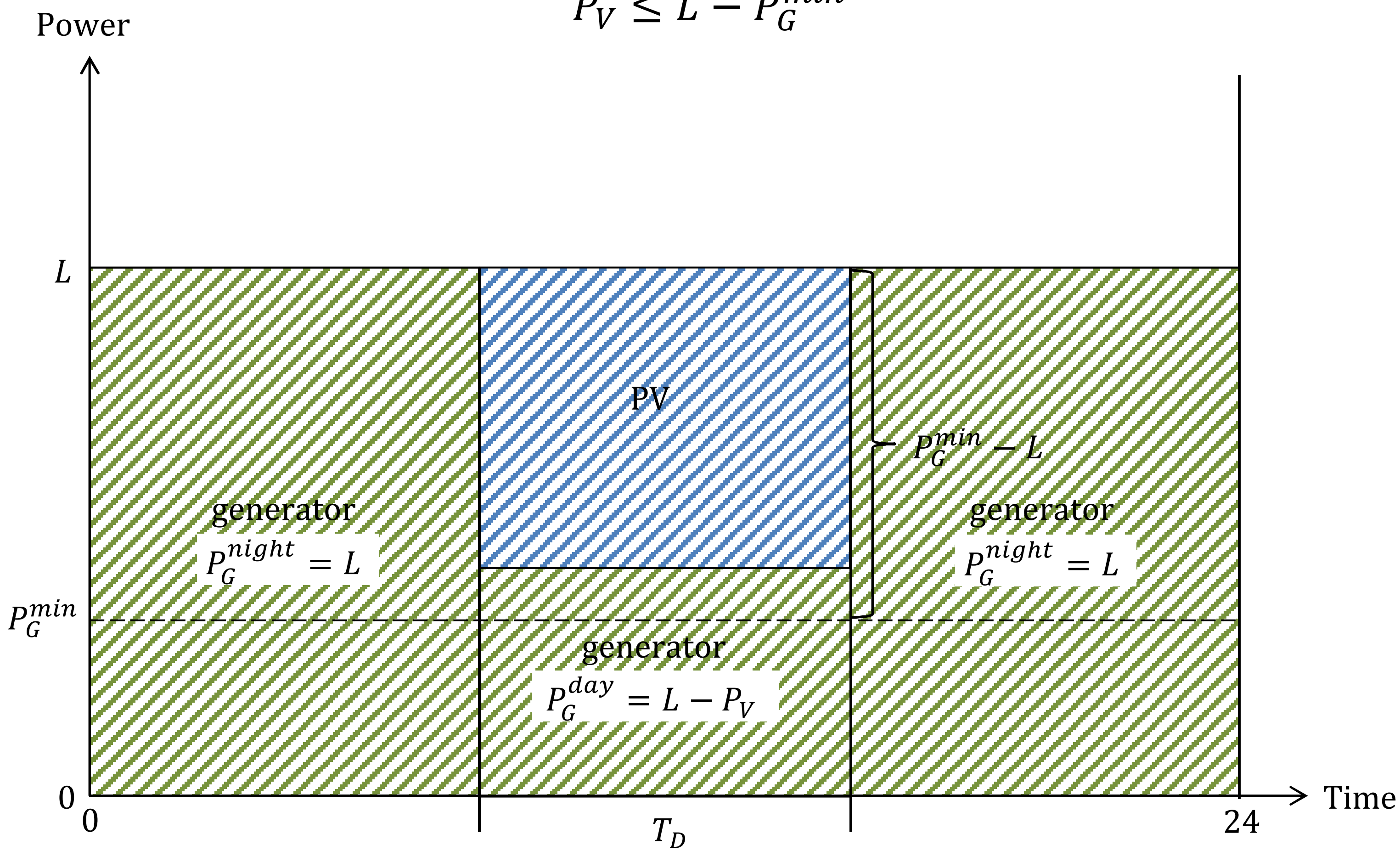


A battery saves fuel with a small load $L < \tilde{L} = \frac{F_0}{F_G} \frac{\eta^4}{1-\eta^4} \cong 3 \frac{F_0}{F_G}$

$\Rightarrow$ typically not the case with a 30kW or 60kW AMMPS (due to a low F_0)

Fuel Use with a Small PV System

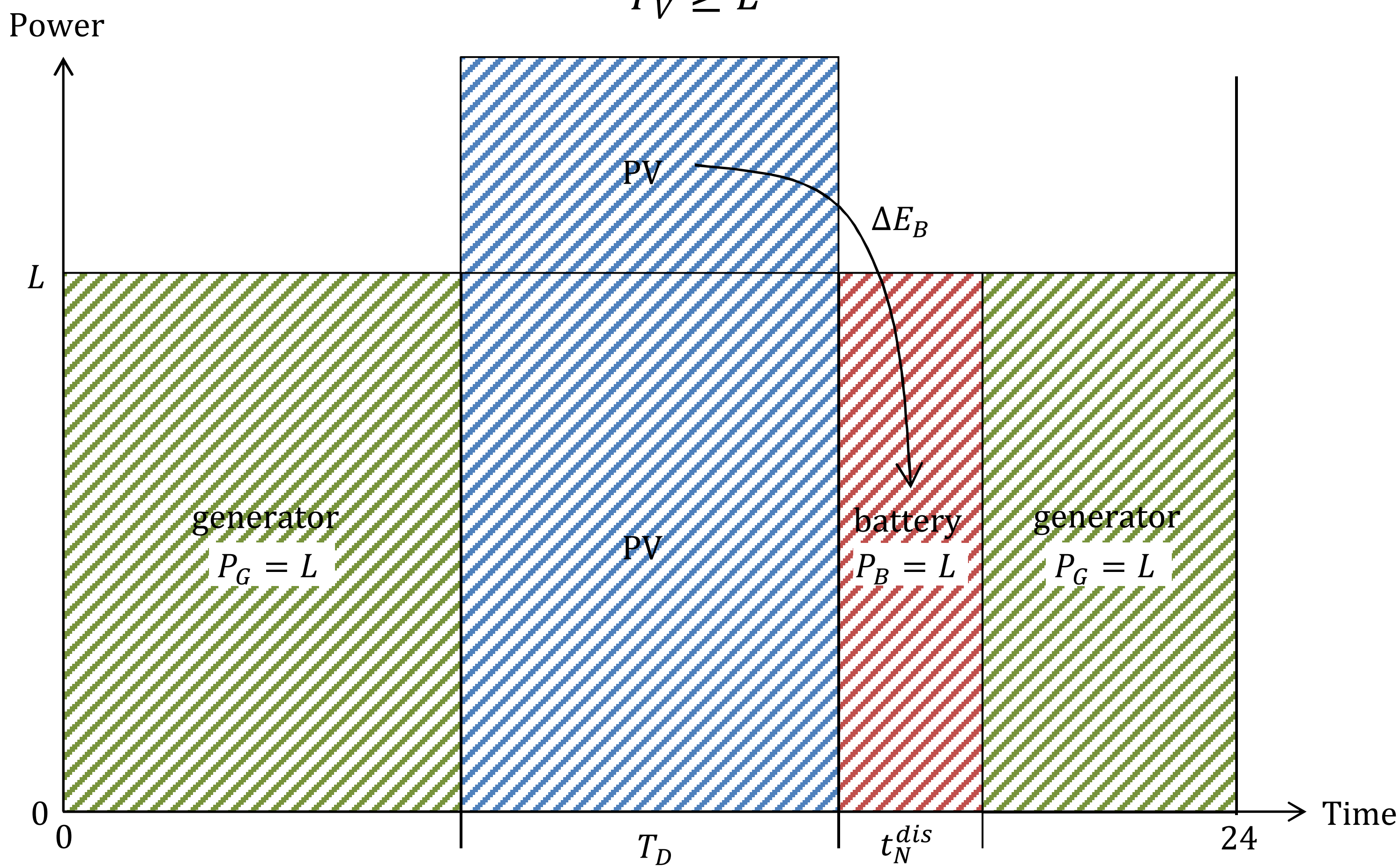
$$P_V \leq L - P_G^{min}$$



$$F = F_0 T + F_G(LT_N + (L - P_V)T_D)$$

Fuel Use with a Large PV System

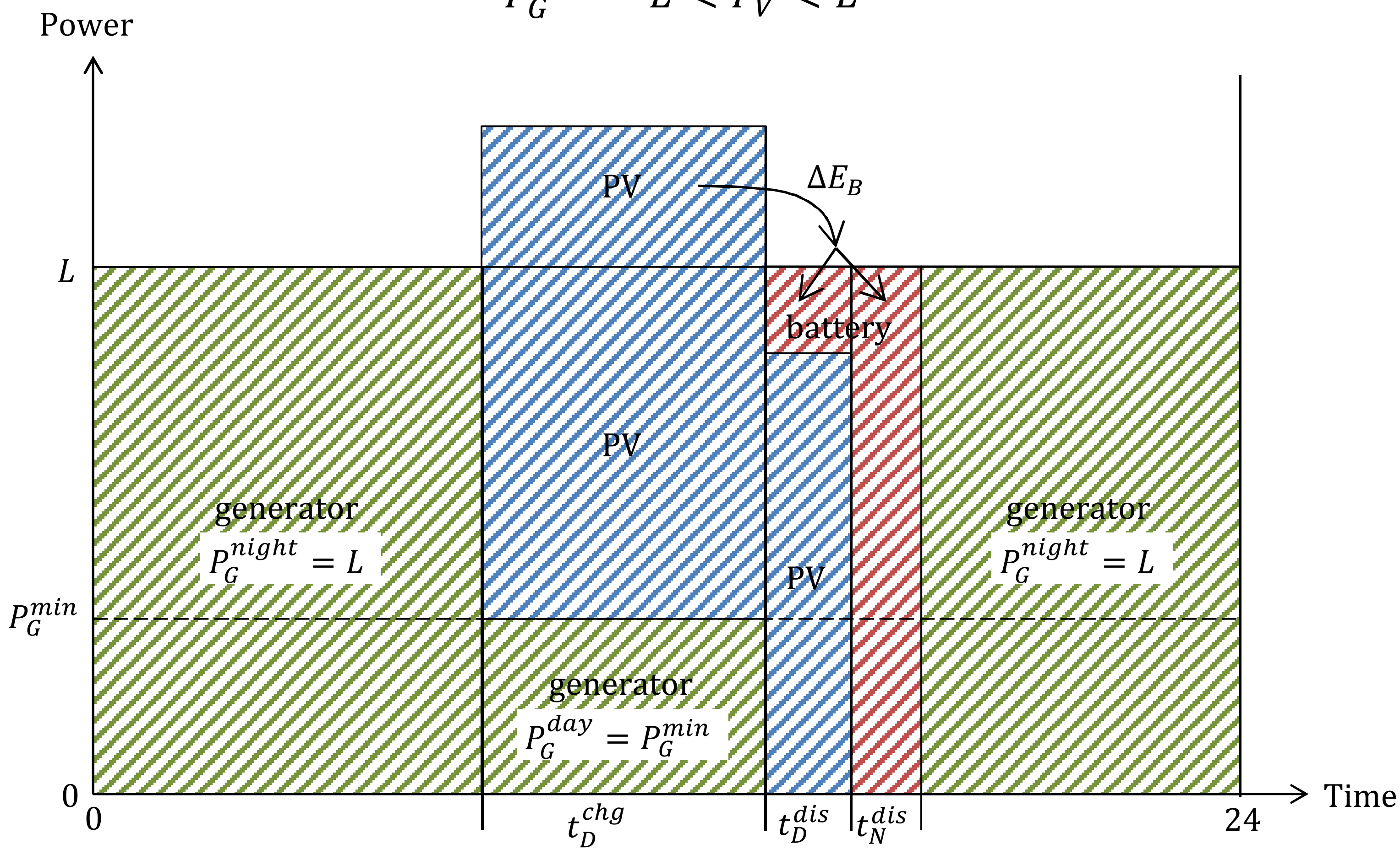
$P_V \geq L$



$$F = (F_0 + F_G L)\cdot\left[T_N - \min\left(T_N,\ \frac{\eta^2 E_B}{L},\ \frac{\eta^4}{L}(P_V - L)T_D\right)\right]$$

Fuel Use with a Medium PV System

$$P_G^{min} - L < P_V < L$$



$$F = (F_0 + F_G L)T_N + \left(F_0 + F_G P_G^{min}\right) \frac{T_D(L - P_V)}{(L - P_V) + \eta^4(P_G^{min} + P_V - L)}$$

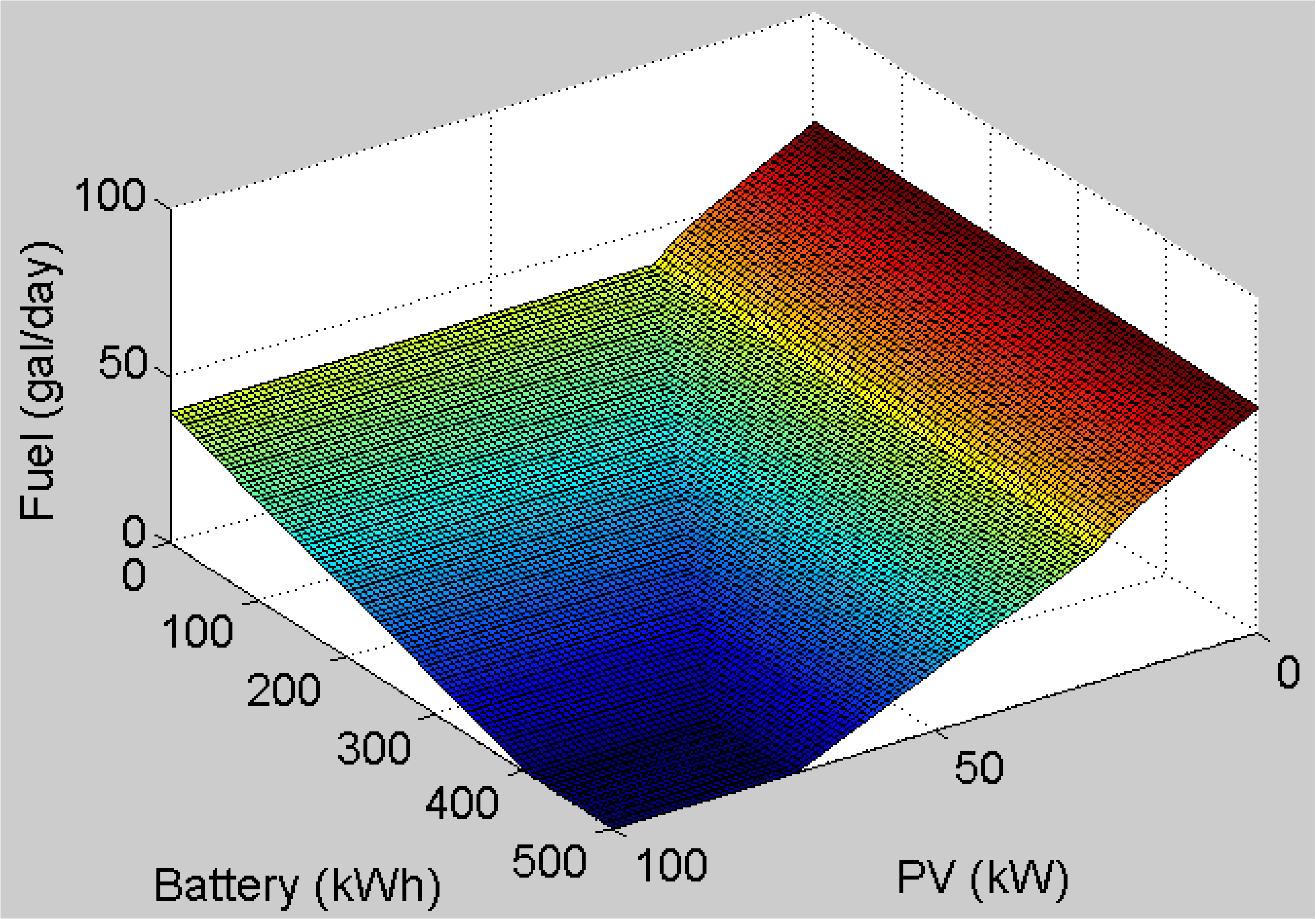
Fuel Use per Day for All Three Cases

$$F = \begin{cases} F_0 T + F_G(LT_N + (L - P_V)T_D) & P_V < L - P_G^{min} \\ (F_0 + F_G L)T_N + \left(F_0 + F_G P_G^{min}\right)\dfrac{T_D(L - P_V)}{(L - P_V) + \eta^4(P_G^{min} + P_V - L)} & L - P_G^{min} < P_V \le L \\ (F_0 + F_G L)\cdot\left[T_N - \min\left(T_N,\ \dfrac{\eta^2 E_B}{L},\ \dfrac{\eta^4}{L}(P_V - L)T_D\right)\right] & P_V > L \end{cases}$$

- Example:

$L = 25$ kW	constant load (24/7)
$P_G^{max} = 30$ kW	generator nameplate rating
$P_G^{min} = 7.5$ kW	minimum generator power
$\eta = 93\%$	efficiency of each of the four stages of energy conversion
$F_0 = 0.3$ gal/hr	constant fuel use per unit time
$F_G = 0.1$ gal/hr/kW	variable fuel use per P_G per unit time
$T_D = 10$ hr	length of "daytime"
$T_N = 24$ hr	length of "nighttime"

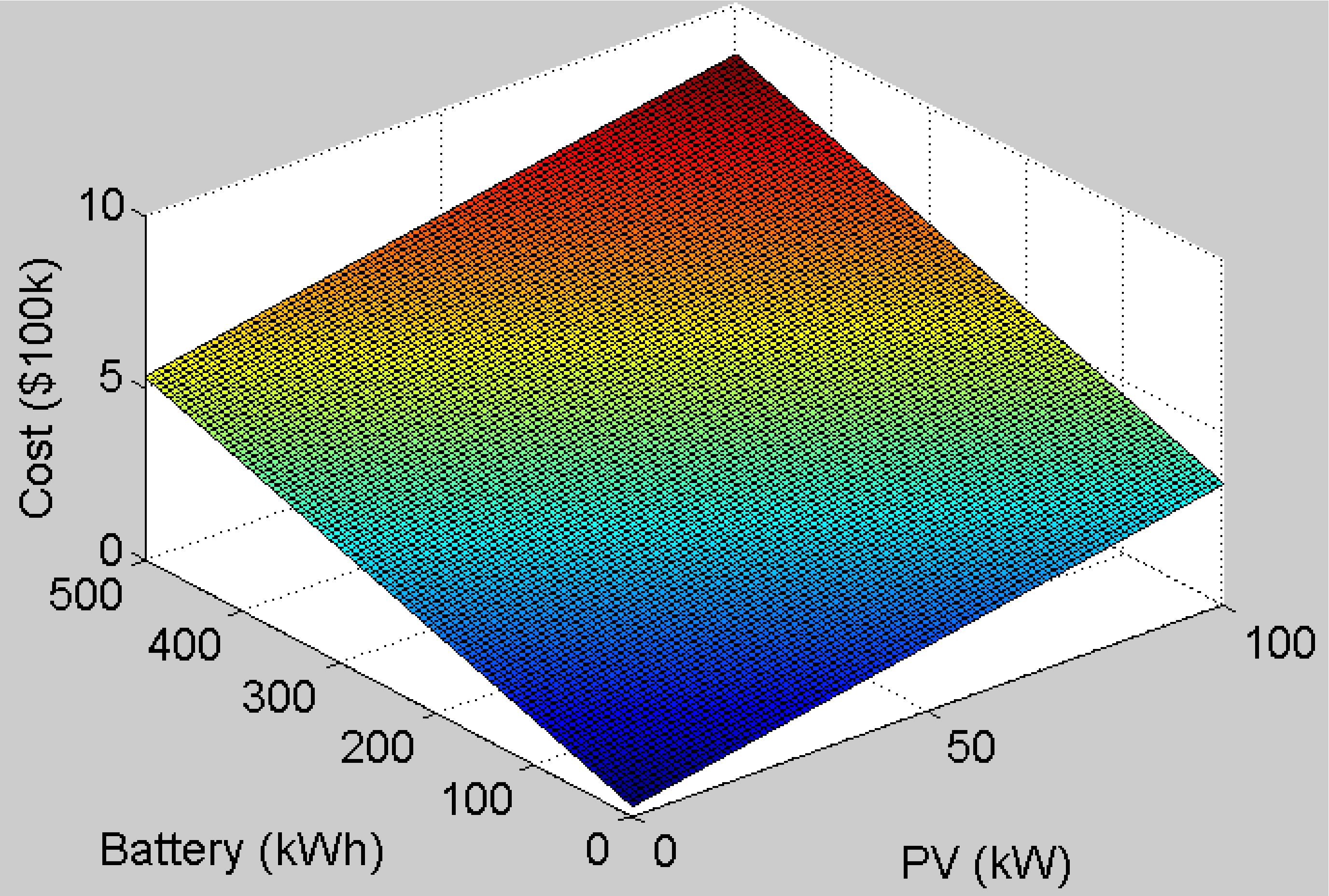
Fuel Use vs. Size of PV and Battery



Multiobjective Optimization

- Want the lowest cost and the lowest fuel use
- Can't have both at the same time, but there are many solutions that are Pareto optimal (or Pareto efficient)
- Pareto optimal solutions are efficient in the sense that they satisfy these properties:
  - Fuel use cannot be lowered without increasing cost, and
  - Cost cannot be lowered without increasing fuel use
- Question: For a given fuel use (constant color) which point has the lowest cost?

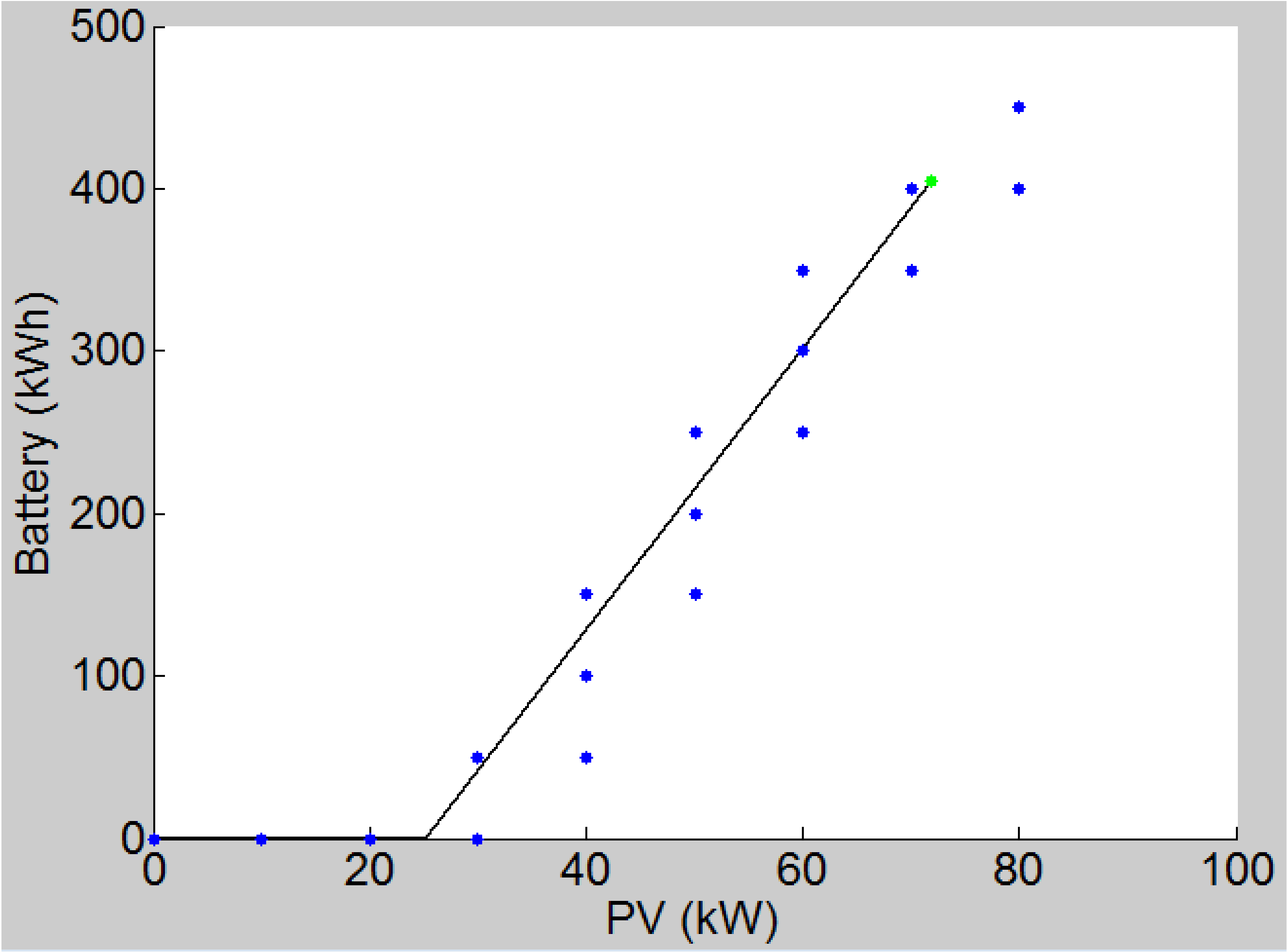
Cost vs. Size of PV and Battery



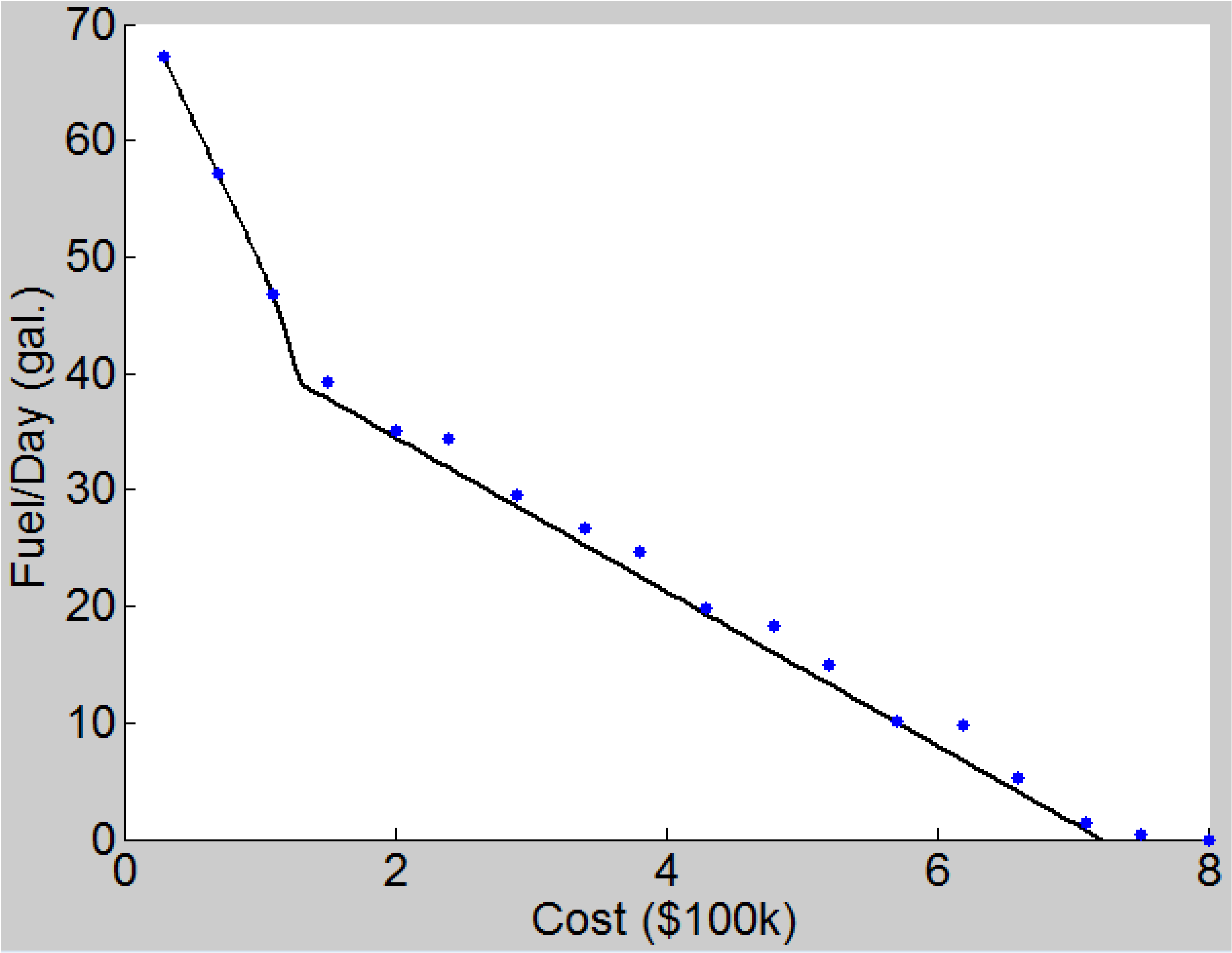
$$C(P_V, E_B) = C_G + C_V P_V + C_B E_B$$

Pareto Frontier: Analytic Solution (Decision Space)

Sandia National Laboratories



Pareto Frontier: Analytic Solution (Performance Space)



Conclusions

- Without PV:
  - Due to large round-trip losses of roughly 25%, a battery does not necessarily save fuel by allowing cycle charging
  - A battery can save fuel when the load is small compared to the power rating of the generator (e.g., less than half of the nameplate rating)
- With PV:
  - A battery typically does not save fuel when power from the PV plus the lowest recommended generator power output never exceeds the load (unless as before, the load is relatively small)
  - A battery can save fuel when this sum exceeds the load
  - It is more fuel efficient to discharge the batteries when the PV can supply the balance of the power than at night when the generator needs to run at higher power anyway
  - There are optimal tradeoffs
  - If the goal is to save fuel, there are (high) limits to the benefits of adding PV and batteries.