ENERGY INSTITUTE
Colorado State University

# Analysis & Recommendations for Entusi Retreat Center Electrical System

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# Electrical System Agenda

- Hybridizing the Entusi Electrical System
- Expanding electrification to nearby villages

Time permitting:

- Simulation overview.
- Failure analysis

# Introduction

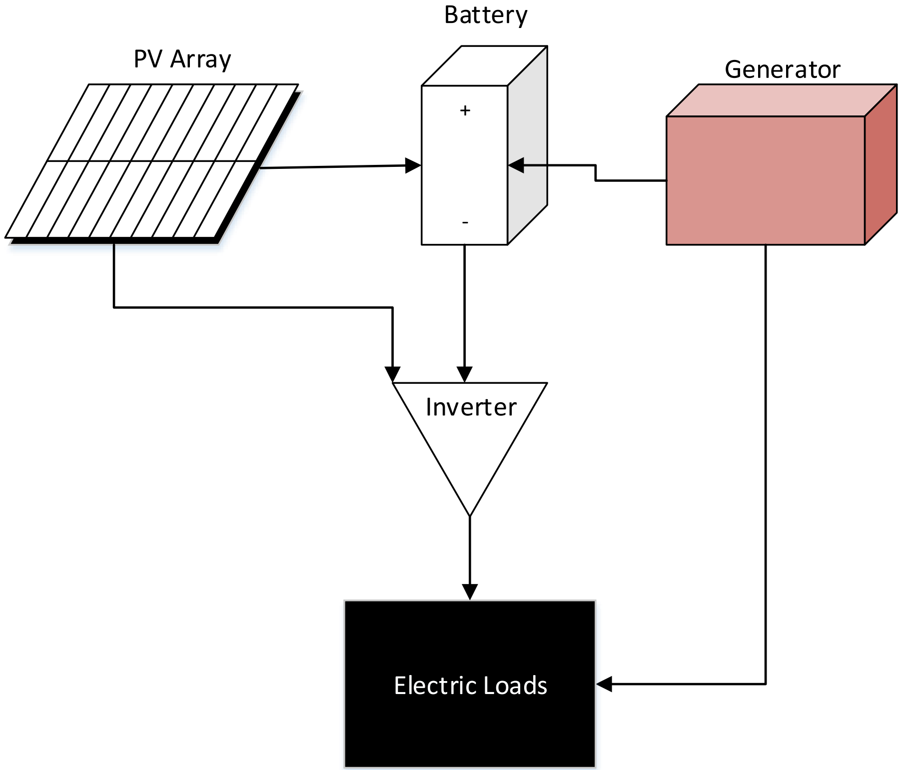
- "Hybridize" Entusi electrical system:
  - Solar photovoltaic (PV) array
  - Engine-generator set (genset)
  - Battery storage

Current system

- Run hours kept at a minimum
- Retreat center without power much of the day
- Noise whenever electricity required

After hybridization:

- Generator started as needed (control to be developed)
- Electricity available all day
- Noise only when generator required



# Introduction

- Goals of hybridization:
  - Reduce generation noise
  - Reduce fossil fuel dependence
    - Improve site sustainability
- Establish Entusi as a model microgrid facility & training location

# Current Entusi Power System

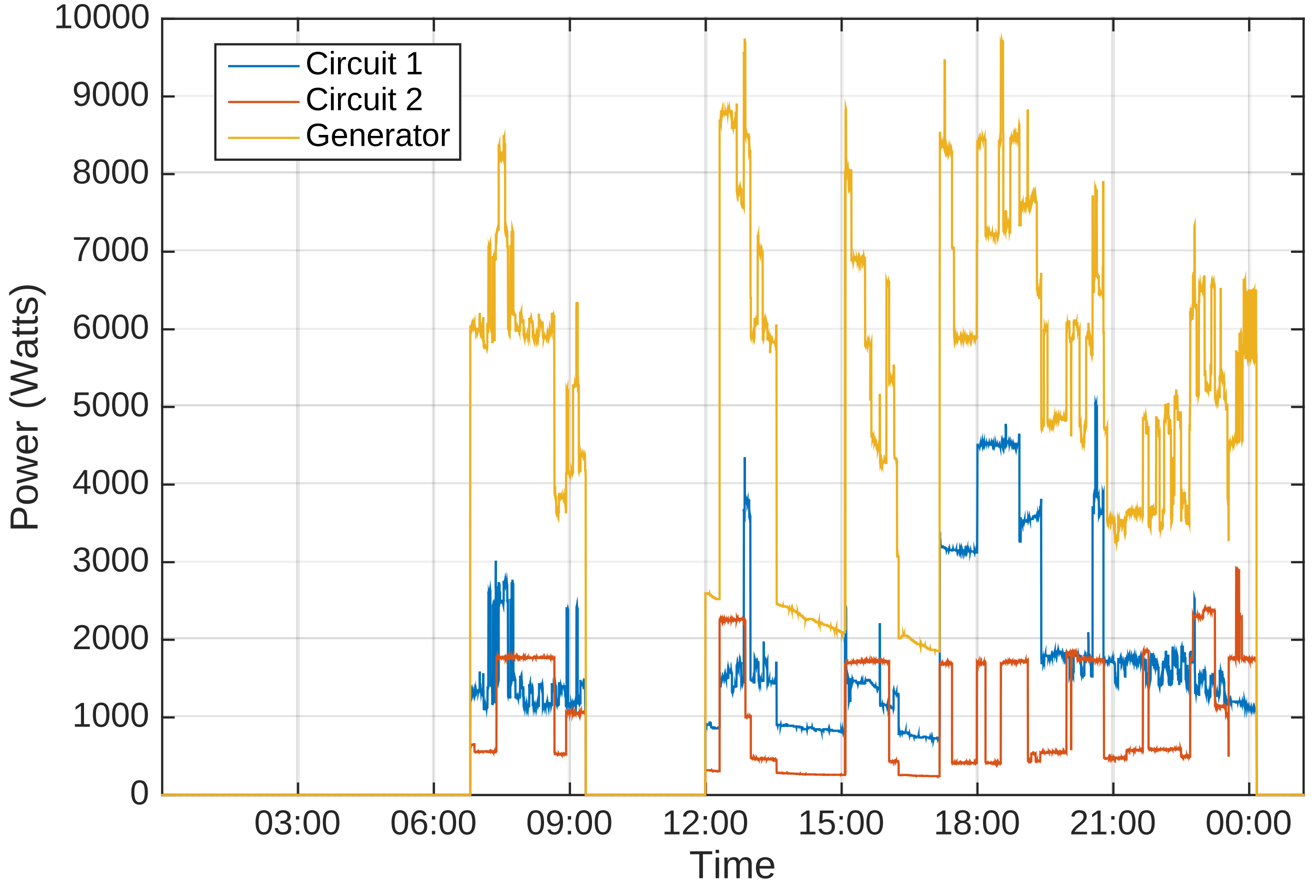
- Two major types of loads:
  - Small, frequently switched
    - Phone and laptop charging
    - Some lights
    - Small appliances
  - Large, on for extended periods
    - Thermal loads:
      - Oven (5.5 kW),
      - Water heaters (7.5 kW total)
    - Some lights

# Current Entusi Power System

| Load Type | Peak Power Draw (kW) |
| --- | --- |
| Lighting | 1.5 |
| Water Heaters | 7.5 |
| Oven | 5.5 |
| Water Pump | 0.5 |
| Power Sockets | 3.0 |
| Refrigeration | 0.5 |
| **Total** | **18.5** |

- Conclusion: Generator is properly sized if all loads are on concurrently (not a likely occurrence)

# Measured Data for Dec. 30, 2016



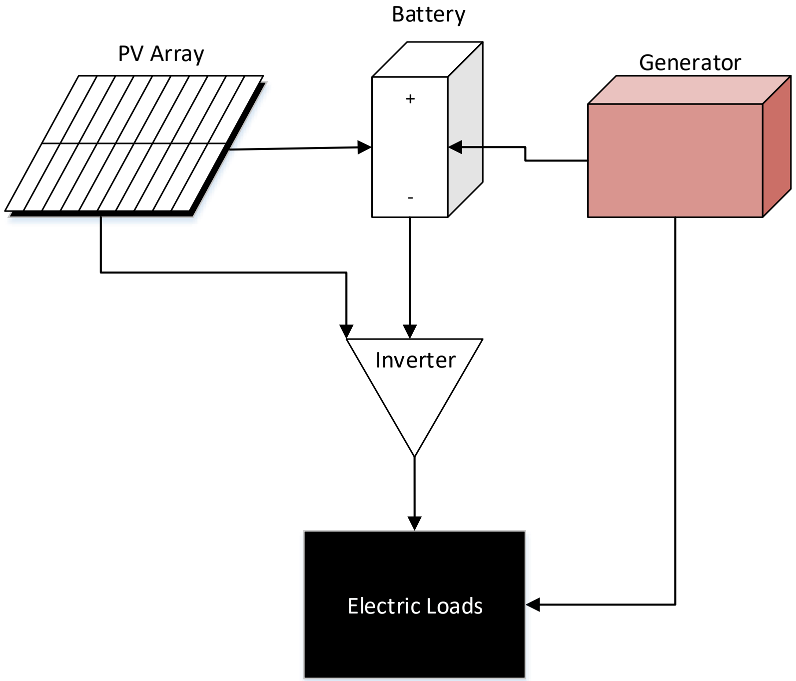

Circuit 1: Dining building; Circuit 2: tent and bathroom on one side

# Approaches for Hybrid System

1) Do nothing
2) Add PV & battery
   – All current loads stay the electric
   – Generator kicks in for larger loads
3) Add PV & battery + *Convert oven and/or water heaters to LPG (propane) units*
   – Engine runs less frequently
   – Reduce size/cost of PV/battery components

# Hybridizing Current System (Case 1)

- Install PV array and battery system (keep existing generator)
  - 18.5 kW PV (~100 square meters)
  - 78 kWh battery



# Hybrid System with Thermal Load Conversion (Cases 2-4)

- Replace oven and/or water heaters with LPG-powered units to reduce electric load
- Install PV array and battery system (keep existing generator)

| | PV Size (kW) | Battery Size (kWh) | PV Array Size (ft^2) |
|---|---|---|---|
| Case 2: Replace Oven | 15.0 | 64.5 | 90 |
| Case 3: Replace Water Heaters | 9.5 | 40 | 60 |
| Case 4: Replace All Heating Loads | 5.5 | 25 | 30 |

# Current and Predicted Fuel Costs

| | | Diesel | LPG |
|---|---|---|---|
| Weekly Cost | Peak (5 mo/yr) | $160 | $43 |
| | Off Peak (7 mo/yr) | $43 | $22 |
| Unit Cost | | $0.90/liter | $3.00/kg |

Reported current weekly fuel costs

| | Generator Weekly Fuel Cost | Appliance Weekly Fuel Cost |
|---|---|---|
| Case 1: No Replacements | $43 | $0 |
| Case 2: Replace Oven | $42 | $62 |
| Case 3: Replace Water Heaters | $0 | $174 |
| Case 4: Replace All Heating Loads | $0 | $236 |

Predicted weekly fuel costs for optimized hybrid system (average)

# Hybrid System Simulation

- Cost Measurements:
  - Levelized cost of electricity ($LCOE_l$, \$/kWh)
    - $LCOE_l = \frac{Implementation\ Cost + Total\ Generator\ Fuel\ Cost}{Total\ Electricity\ Consumed}$
  - Levelized cost of energy ($LCOE_n$, \$/kWh)
    - $LCOE_n = \frac{Implementation\ Cost + Total\ Fuel\ Costs}{Total\ Electricity\ Consumed + Total\ Heat\ Consumed}$
    - Applicable when thermal loads served by LPG units

10% discount rate, 3% diesel fuel inflation

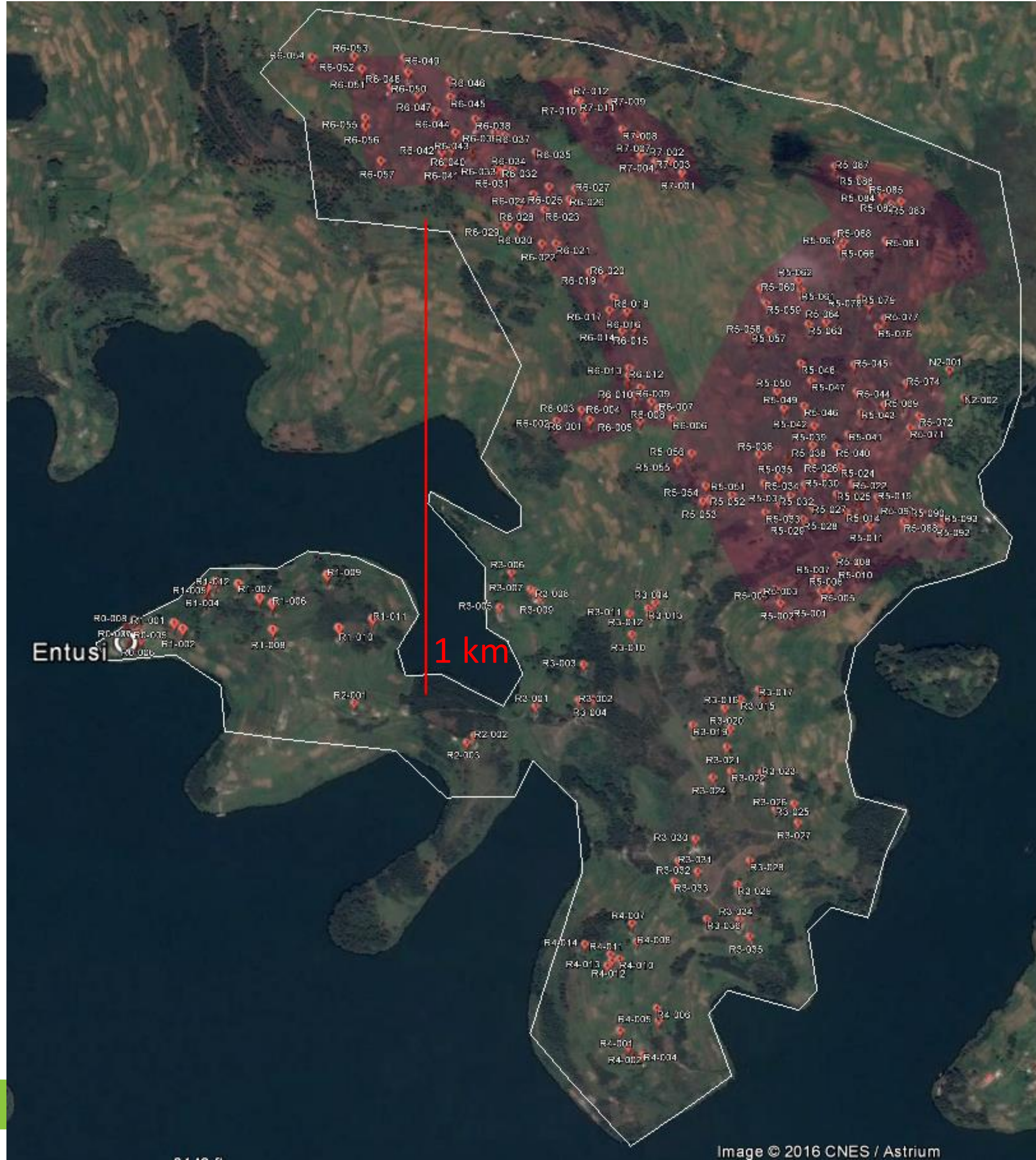
# Hybrid System Lowest Cost Configurations

| | PV Size (kW) | Battery Size (kWh) | Generator Hours (avg/day) | Install Cost | LCOEI ($/kWh) | Implementation + Generator Run Cost | LCOEn ($/kWh) | Implementation + Total Fuel Cost |
|---|---|---|---|---|---|---|---|---|
| Case 0: No Hybrid System | 0.0 | 0 | 10.0 | $0 | $0.758 | $123,000 | $0.758 | $123,000 |
| Case 1: No Replacements | 18.5 | 78.0 | 0.2 | $86,000 | $0.556 | $91,000 | $0.556 | $91,000 |
| Case 2: Replace Oven | 15.0 | 64.5 | 0.0 | $81,000 | $0.605 | $85,000 | $0.570 | $121,000 |
| Case 3: Replace Water Heaters | 9.5 | 40 | 0.0 | $54,000 | $0.821 | $57,000 | $0.363 | $119,000 |
| Case 4: Replace All Heating Loads | 5.5 | 25 | 0.0 | $42,000 | $0.990 | $45,000 | $0.380 | $142,000 |

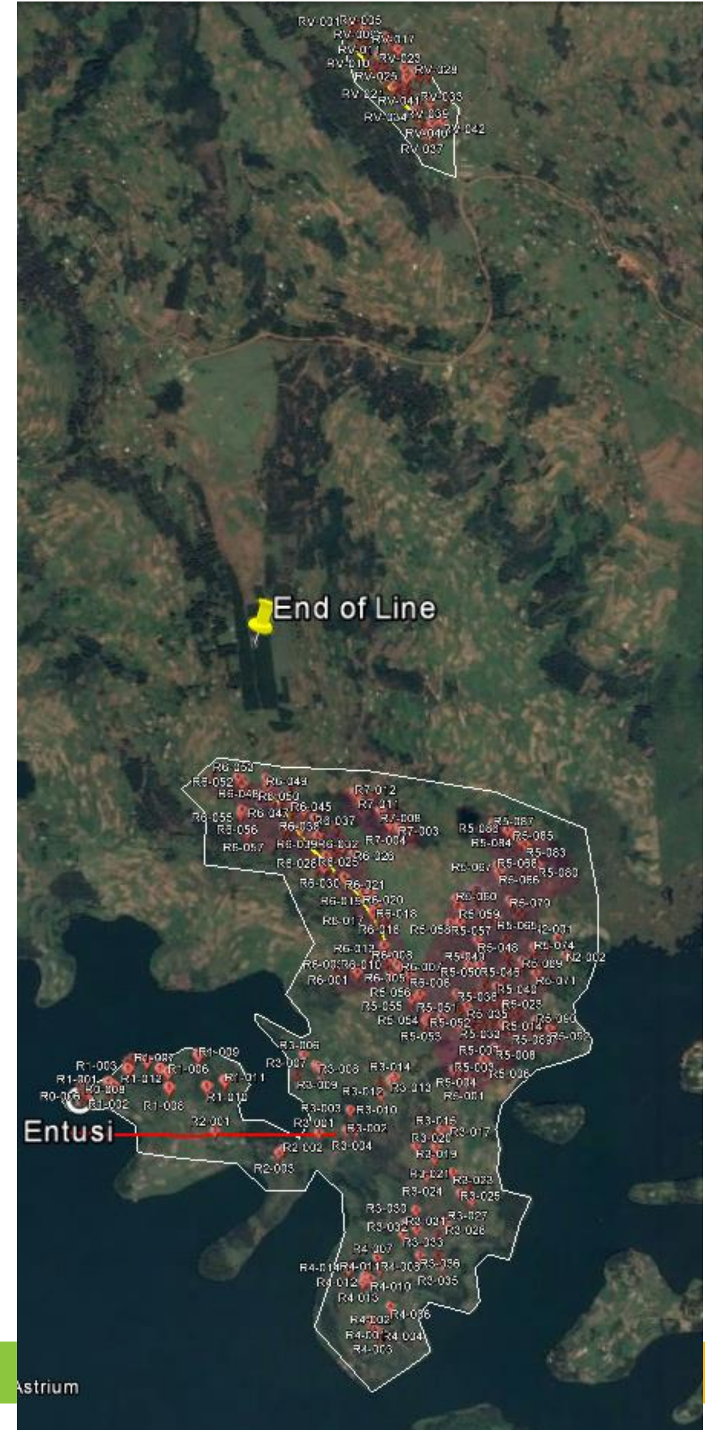
# ELECTRIFICATION OF SURROUNDING AREAS

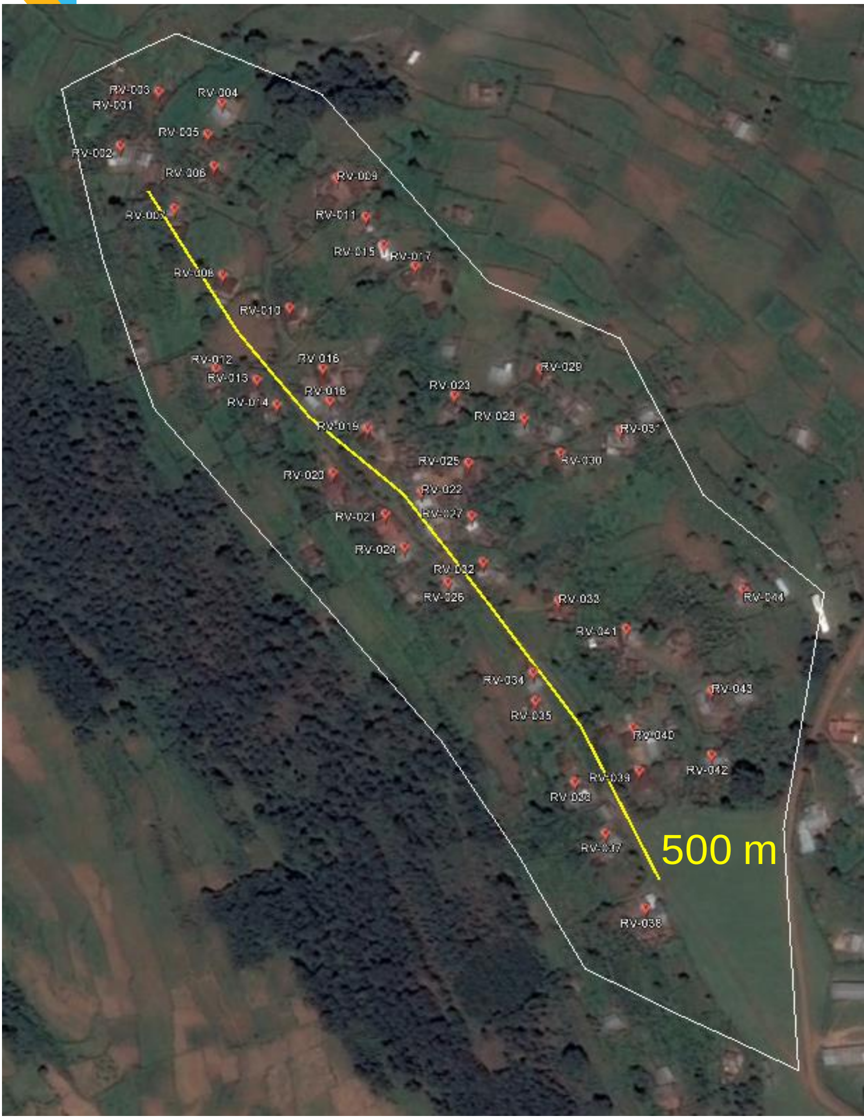
# Electrification of Surrounding Areas

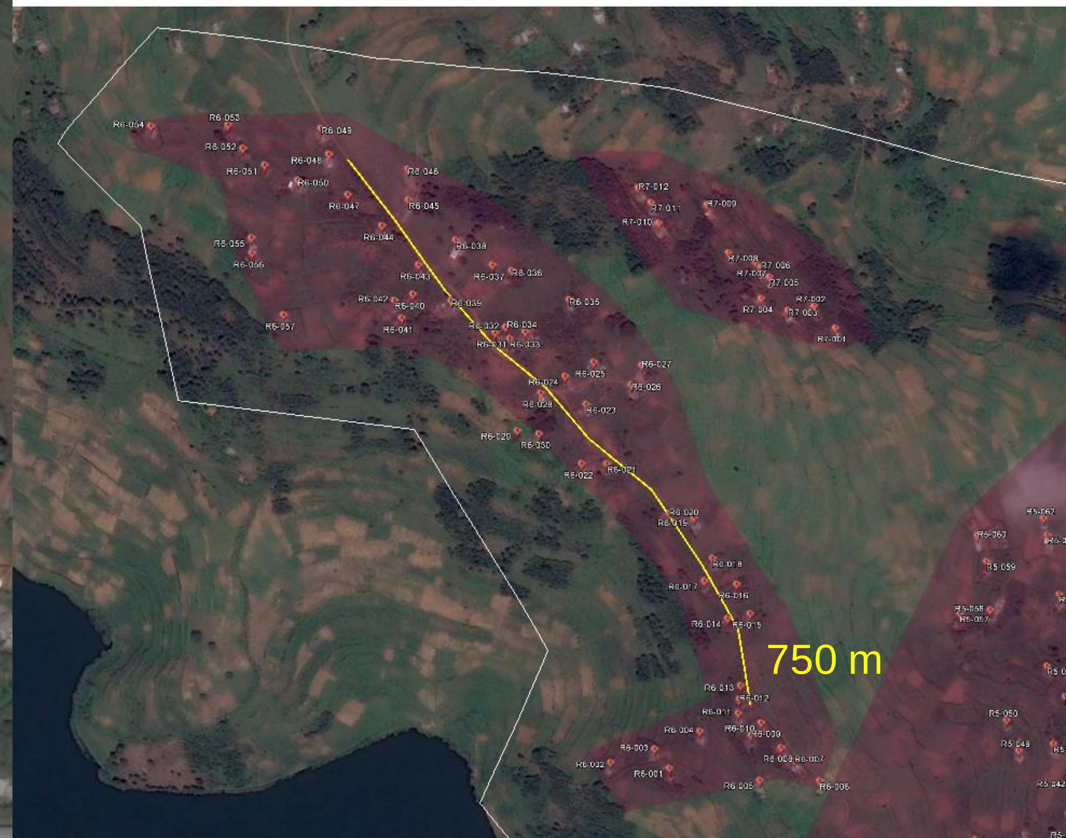
- During CSU's visit, performed survey of nearby residential areas
- Main observations:
  - 1) Housing density close to Entusi is too low to merit connecting to Entusi's system
  - 2) Highest housing density areas also show greatest capability/desire to purchase electricity (some already have solar panels)
  - 3) Utility line ends just 0.5 km from high density housing area (major risk factor)

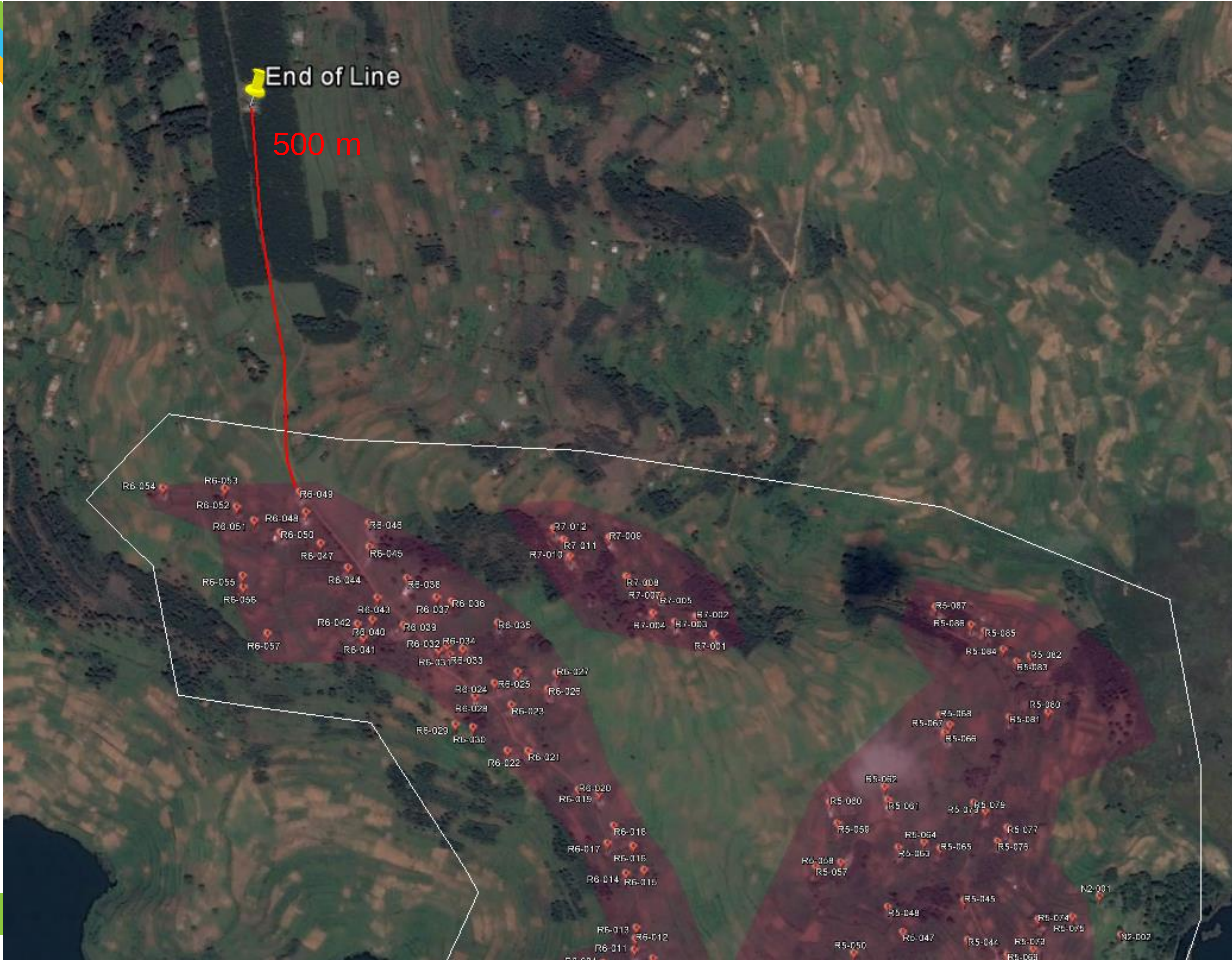

Entusi
1 km
Image © 2016 CNES / Astrium


Entusi
2016-12-30 13:28:28
2016-12-31 14:13:29
6 CNES / Astrium


End of Line
Entusi
Astrium


500 m

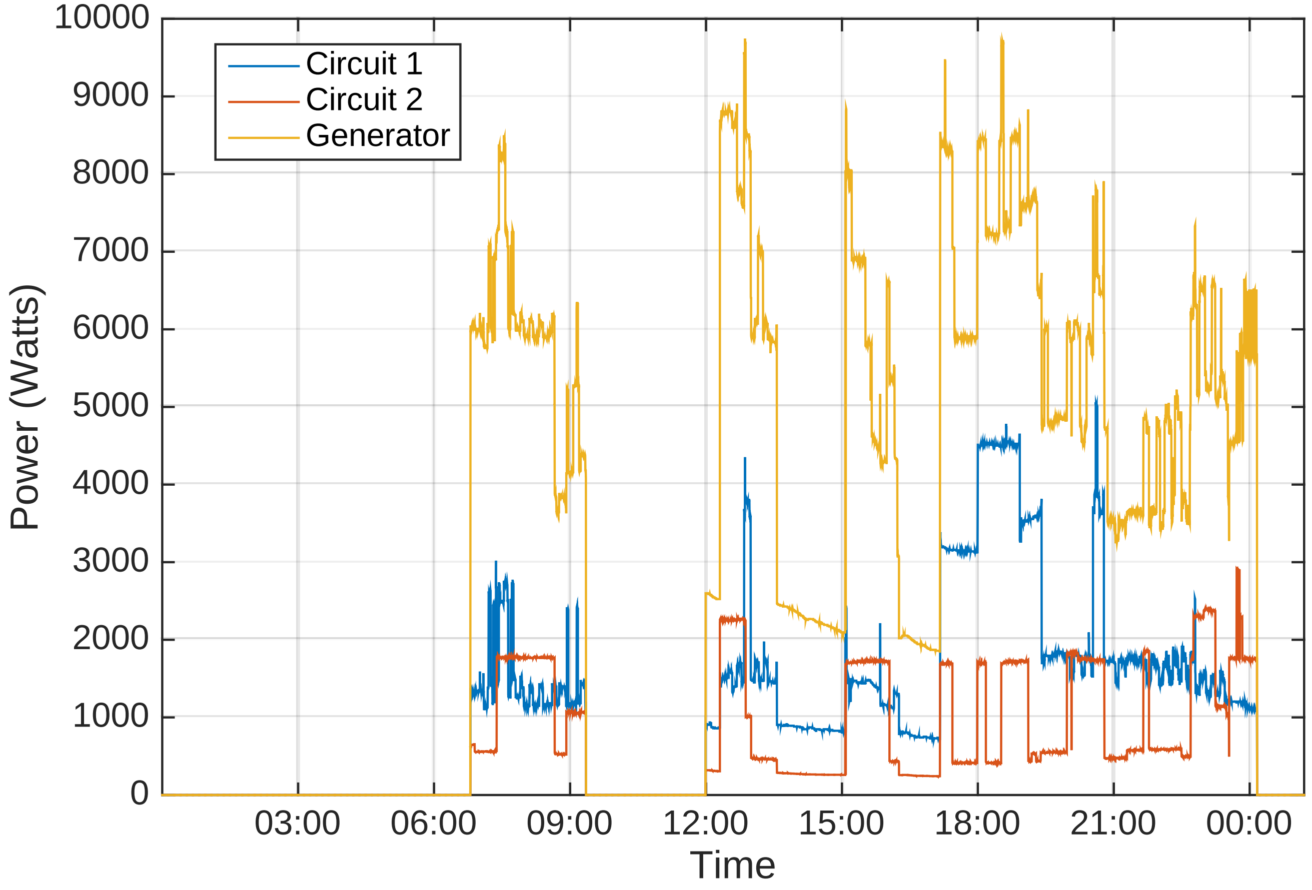

750 m


End of Line
500 m

How we got the answers

# SIMULATION OVERVIEW

# Measured Data for Dec. 30, 2016



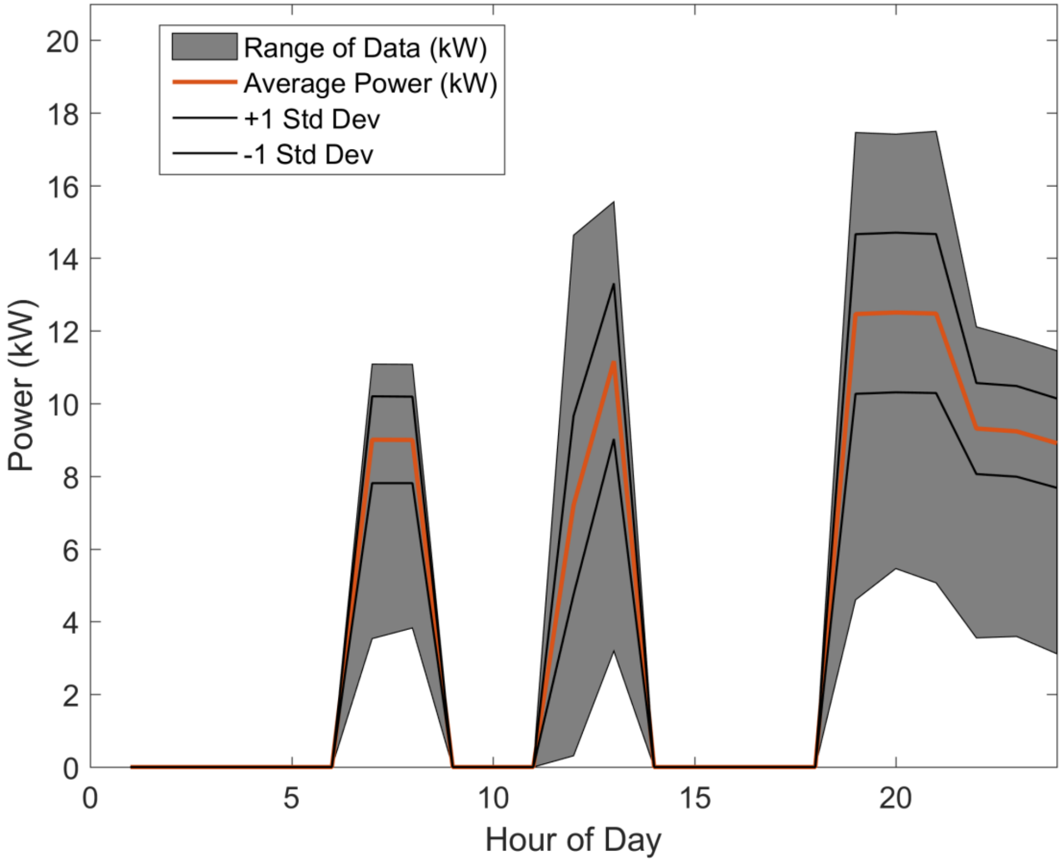

Circuit 1: Dining building; Circuit 2: tent and bathroom on one side

# Data Description: Load Measurements

- Power draws measured during CSU's visit: Dec. 30 and 31, 2016
- Useful for validating on/off times for different loads
- Limits to applicability of data
  - Not typical loading during visit
  - Small sample (only 2 full days)
  - Uncertainty in sensor measurement

# Load Simulation

- Peak season profile for current load configuration:



# Simulation and Analysis

- 2 components to simulation:
  - 1) Load simulation
  - 2) Hybrid system generation simulation
- Both components: hourly simulation for a span of 20 years

# Load Simulation

- Probability that each load is on during each hour of the day
- Peak and off-peak seasons
  - – Staff testimony, observations from visit, measured data
- Create hourly load profile for 20 years

# Hybrid System Simulation

- Use solar irradiation data from Kigali, RW
- Each hour:
  - 1) Power from PV serves load
  - 2) Extra PV power charges battery *or* extra load served by discharging battery
  - 3) Generator serves remaining load

# Hybrid System Simulation

- Salient outputs:
  - Levelized cost of electricity ($LCOE_l$, \$/kWh)
    - $LCOE_l = \frac{Implementation\ Cost + Total\ Generator\ Fuel\ Cost}{Total\ Electricity\ Consumed}$
    - 10% discount rate, 3% diesel fuel inflation
  - Total installation and running costs
  - Average daily generator runtime (hours)
  - Levelized cost of energy ($LCOE_n$, \$/kWh)
    - $LCOE_n = \frac{Implementation\ Cost + Total\ Fuel\ Costs}{Total\ Electricity\ Consumed + Total\ Heat\ Consumed}$
    - Applicable when thermal loads served by LPG units

# Hybrid System Simulation

- Costs estimated using unit prices:
  - – PV array: $2/watt ($2,000/kW)
  - – Battery: $350/kWh
  - – Generator fuel: $2/hour generator runs
    - Assuming constant rate of fuel consumption, as reported by staff
- Current system estimated cost of electricity: ~$0.35/kWh

# Hybrid System Simulation

- Simulation run for many combinations of PV array and battery sizing
- Optimal configuration for each case: lowest $LCOE_l$

# Hybrid System Lowest Cost Configurations

| | PV Size (kW) | Battery Size (kWh) | Generator Hours (avg/day) | Install Cost | $LCOE_I$ (\$/kWh) | Implementation + Generator Run Cost | $LCOE_n$ (\$/kWh) | Implementation + Total Fuel Cost |
|---|---|---|---|---|---|---|---|---|
| Case 1: No Replacements | 18.5 | 78.0 | 0.2 | $86,000 | $0.556 | $91,000 | $0.556 | $91,000 |
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# Hybrid System Optimal Configurations

- Overall optimum configuration (minimum *LCOE*$_l$):
  - Case 1, retain electric oven and water heaters
  - $0.556/kWh
  - PV array: 18.5 kW ($37,000)
  - Battery: 78 kWh ($27,300)
  - Generator: runs average of 0.2 hours/day (i.e. runs rarely to serve peak loads)

# Other Considerations

- $LCOE_I$ may not be most important metric
- E.g.: minimize up-front cost, minimize $LCOE_n$

| | Initial Implementation Cost | *LCOEn* ($/kWh) |
|---|---|---|
| Case 1: No Replacements | $86,000 | $0.556 |
| Case 2: Replace Oven | $81,000 | $0.570 |
| Case 3: Replace Water Heaters | $54,000 | $0.363 |
| Case 4: Replace All Heating Loads | $42,000 | $0.380 |

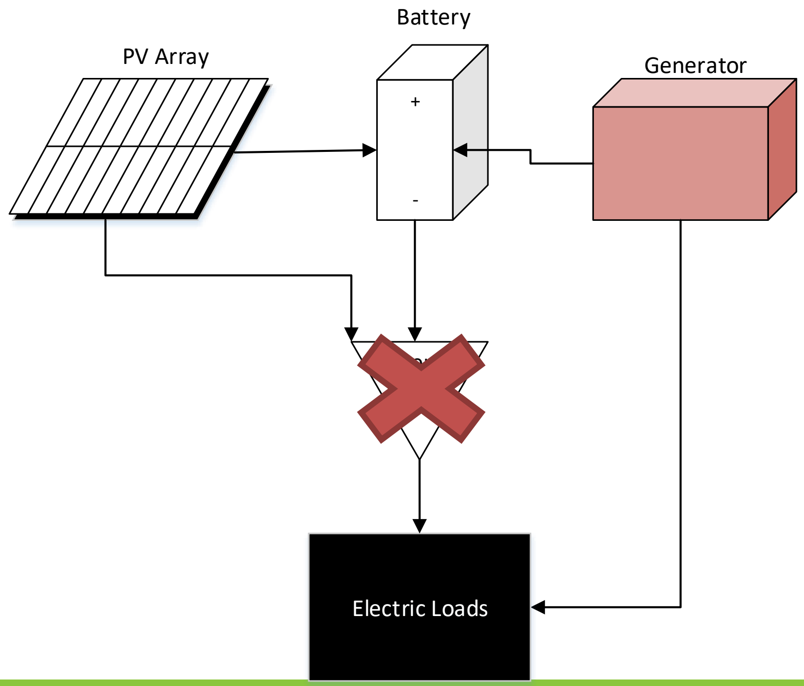
# ADDITIONAL ANALYSIS

# Failure Analysis

- Selection of potential failure modes for hybrid system:
  - 1) Inverter failure
  - 2) Battery failure
  - 3) Generator failure

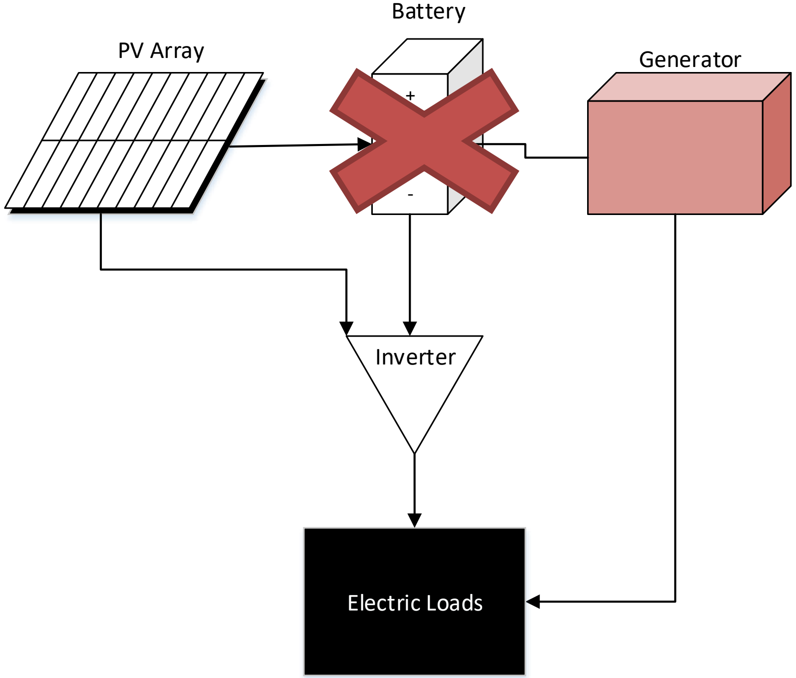
# Inverter Failure

- No power from PV/battery system
- Generator serves load independently
  - Not a problem if keep current generator



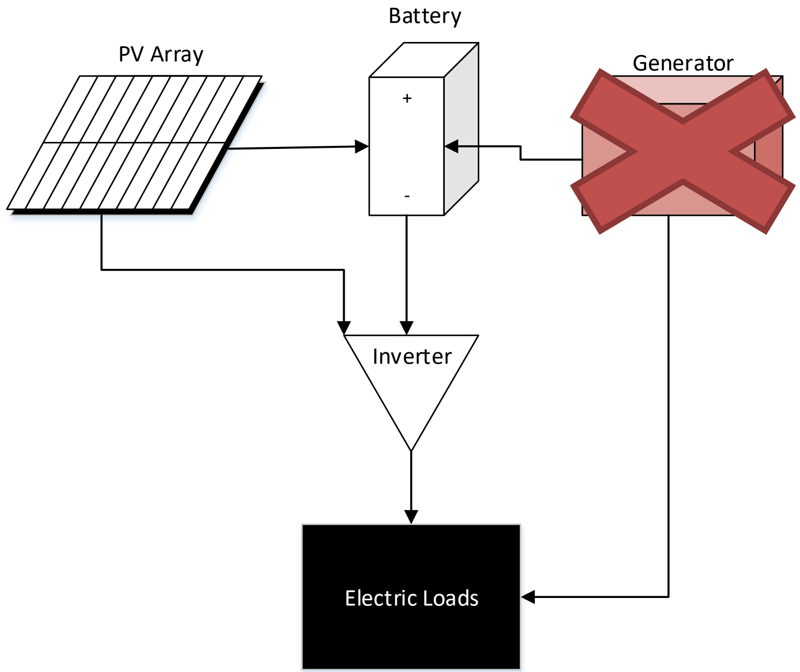
# Battery Failure

- No electricity storage
- PV and generator must serve load
  - Generator must run more



# Generator Failure

- PV/battery system must attempt to serve load
  - Current system has no safeguard against this: hybrid system more robust



# Thank You!

## Contact

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