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

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Peak Power Draw (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>1.5</td>
</tr>
<tr>
<td>Water Heaters</td>
<td>7.5</td>
</tr>
<tr>
<td>Oven</td>
<td>5.5</td>
</tr>
<tr>
<td>Water Pump</td>
<td>0.5</td>
</tr>
<tr>
<td>Power Sockets</td>
<td>3.0</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.5</strong></td>
</tr>
</tbody>
</table>

• 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)

<table>
<thead>
<tr>
<th></th>
<th>PV Size (kW)</th>
<th>Battery Size (kWh)</th>
<th>PV Array Size (ft^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2: Replace Oven</td>
<td>15.0</td>
<td>64.5</td>
<td>90</td>
</tr>
<tr>
<td>Case 3: Replace Water Heaters</td>
<td>9.5</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Case 4: Replace All Heating Loads</td>
<td>5.5</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>
## Current and Predicted Fuel Costs

<table>
<thead>
<tr>
<th>Weekly Cost</th>
<th>Diesel</th>
<th>LPG</th>
<th>Generator Weekly Fuel Cost</th>
<th>Appliance Weekly Fuel Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (5 mo/yr)</td>
<td>$160</td>
<td>$43</td>
<td>$43</td>
<td>$0</td>
</tr>
<tr>
<td>Off Peak (7 mo/yr)</td>
<td>$43</td>
<td>$22</td>
<td>$42</td>
<td>$62</td>
</tr>
<tr>
<td>Unit Cost</td>
<td>$0.90/liter</td>
<td>$3.00/kg</td>
<td>$0</td>
<td>$174</td>
</tr>
<tr>
<td>Case 1: No Replacements</td>
<td>$43</td>
<td>$0</td>
<td>Case 2: Replace Oven</td>
<td>$42</td>
</tr>
<tr>
<td>Case 3: Replace Water Heaters</td>
<td>$0</td>
<td>$174</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4: Replace All Heating Loads</td>
<td>$0</td>
<td>$236</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reported current weekly fuel costs

Predicted weekly fuel costs for optimized hybrid system (average)
Hybrid System Simulation

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

10% discount rate, 3% diesel fuel inflation
## Hybrid System Lowest Cost Configurations

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

500 m
How we got the answers

SIMULATION
OVERVIEW
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 ($LCOE_l$, $$/kWh$)
    • $LCOE_l = \frac{\text{Implementation Cost} + \text{Total Generator Fuel Cost}}{\text{Total Electricity Consumed}}$
  • 10% discount rate, 3% diesel fuel inflation
  – Total installation and running costs
  – Average daily generator runtime (hours)
  – Levelized cost of energy ($LCOE_n$, $$/kWh$)
    • $LCOE_n = \frac{\text{Implementation Cost} + \text{Total Fuel Costs}}{\text{Total Electricity Consumed} + \text{Total Heat Consumed}}$
  • 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 $LCOE_i$
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<th>$LCOE_i$ ($/kWh)</th>
<th>Implementation + Generator Run Cost</th>
<th>$LCOE_n$ ($/kWh)</th>
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Hybrid System Optimal Configurations

• Overall optimum configuration (minimum $LCOE_i$):
  – 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 the most important metric
- E.g., minimize up-front cost, minimize \( LCOE_n \)

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<th>( LCOE_n ) ($/kWh)</th>
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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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