Tetiaroa Energy Storage System

- *Estimated ZBB Zinc Bromide Battery Performance and Costs*

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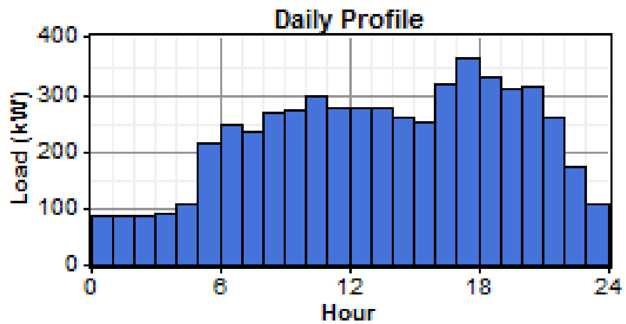
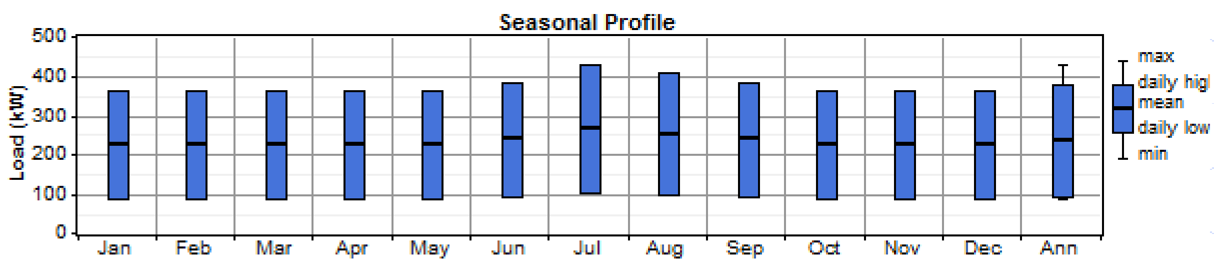
Island Load and Diesel Generation Assumptions

Estimated Electrical Load

- The estimated electricity use for Tetiaroa was based on data provided in "*simulation energie site 500 kW photovoltaique*"
- This data was used to create a model of the average electric demand for each hour of the year
- Modeled electricity load:
  - Average daily energy use: 5,698 kWh
  - Average power demand: 237 kW
  - Peak power demand: 427 kW
  - Load factor: 55%



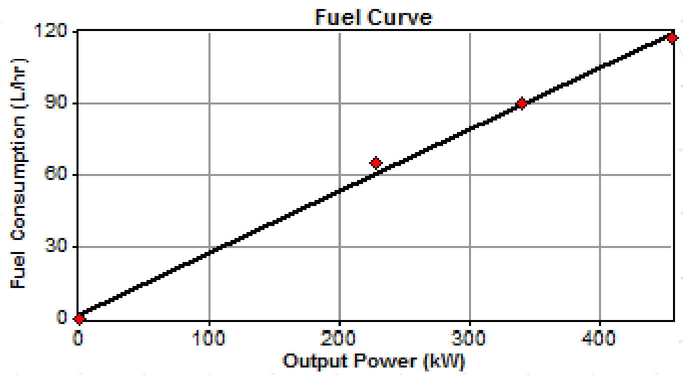
Average daily load profile



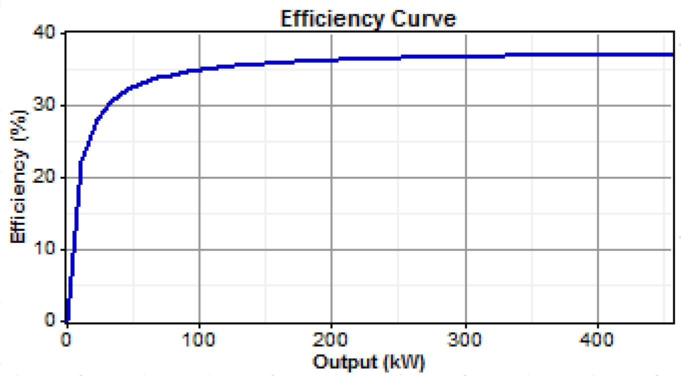
Seasonal load variation

Diesel Generation

- It was assumed that backup generation will be met via (2) 455 kW diesel generator sets
- These generator sets were modeled using data available for the Caterpillar (CAT) DM8154 455 kW prime power model (455 ekW, 569 kVA, 480 VAC)
- It is assumed that each gen set has:
  - Minimum load factor: 30%
  - Operational life: 30,000 hrs
- The modeled fuel and efficiency curves are shown here



Modeled 455kW Gen set fuel curve



Modeled 455kW Gen set efficiency curve

http://rael.berkeley.edu

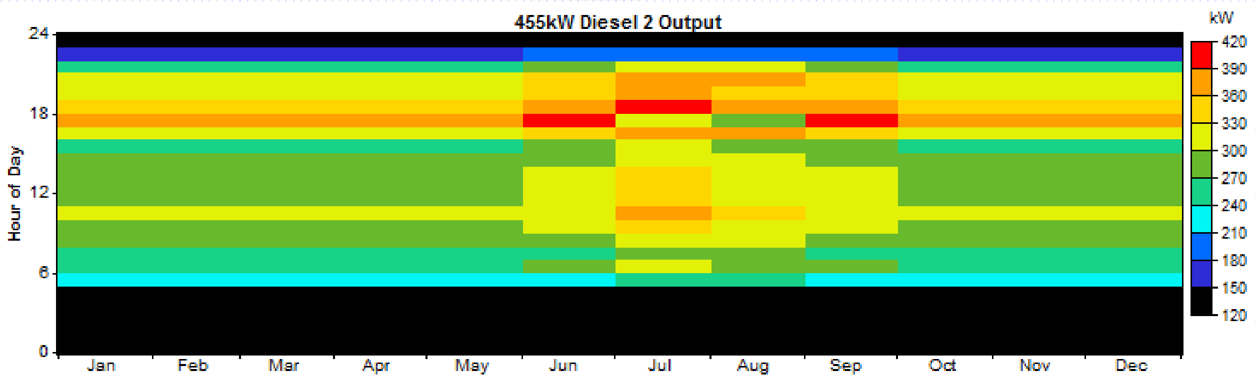
Diesel Generation

- Emissions factors were modeled based on data obtained from Caterpillar on a similar generator set (320 kW):
  - Carbon monoxide: 2.67 g/L of fuel
  - Unburned hydrocarbons: 0.267 g/L of fuel
  - Particulate matter (PM): 0.178 g/L of fuel
  - Proportion of fuel sulfur converted to PM: 2.2%
  - Nitrogen oxides: 14.52 g/L of fuel
- The diesel fuel properties were modeled based on the following values, representative for a small island refinery:
  - Lower heating value: 42.5 MJ/kg
  - Density: 871 kg/m^3
  - Carbon content: 88%
  - Sulfur content: 0.145%
- These data are used to generate the carbon dioxide equivalent (CO_{2e}) emissions for each model

Diesel-only Model

- A hypothetical model was created to show the diesel use and emissions if the electrical load was met only by the generator sets. The model results are used subsequently to calculate emission reductions from the renewable systems

- Model results (summary):
  - Fuel use: 595,000 L/yr
  - CO_{2e} Emissions: 4,400 tonnes/yr
  - Operational lifetime of generator sets (assuming two identical generator sets, switched every 2-4 weeks): ~7yrs

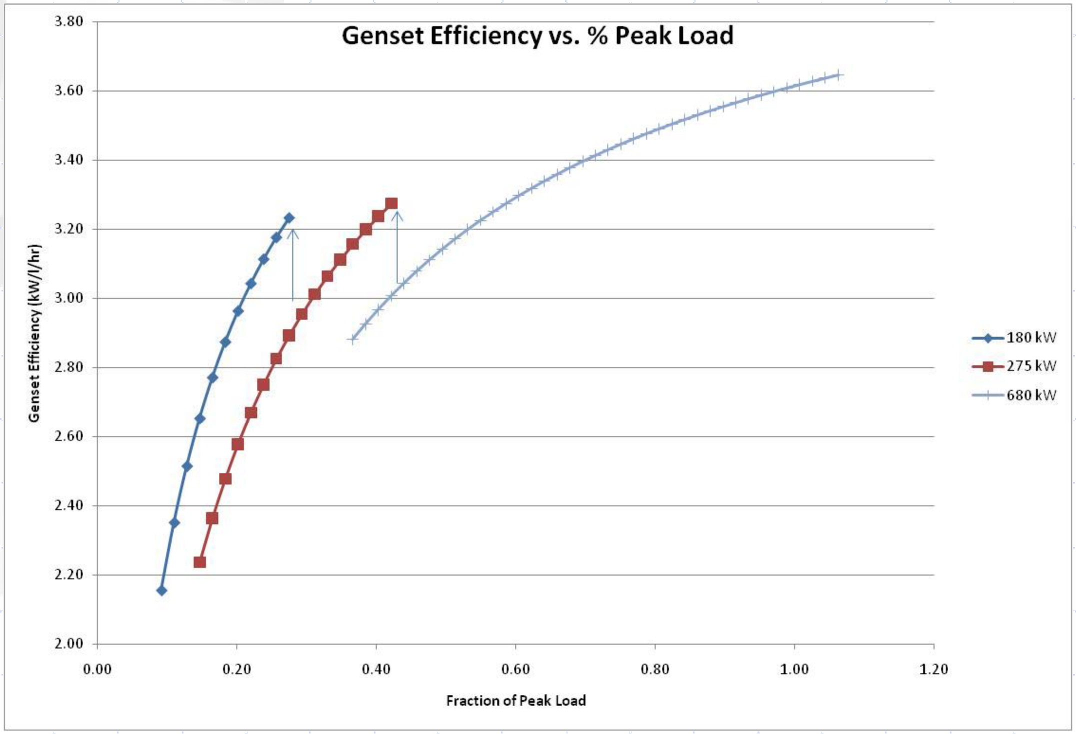


Modeled 455kW gen set output power

Alternative Diesel Sizing

- A possible alternative to having multiple 455 kW gen sets for backup generation would be to have a few gen sets of differing sizes. The plot below shows the increase in efficiency (and hence, decreased fuel use) that would result from switching to a smaller generator set when the load is decreased

- The multiple-diesel solution shown would result in a fuel savings of 64,000 L of fuel per year and an 8% reduction in emissions



Efficiency Increase from Multiple Gen Set Design

Photovoltaic System Assumptions

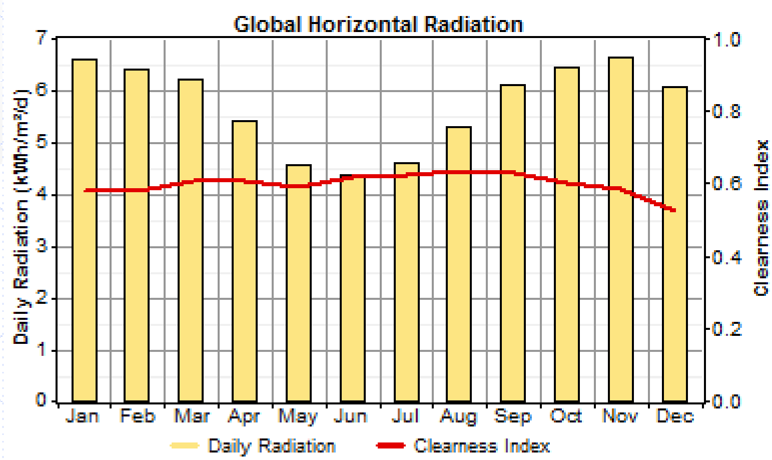
Solar Energy Resource

- The solar energy resource on Tetiaroa was modeled based on insolation (incident solar radiation) data available from NASA
- This data is based on site location (lat / long), and is used along with the temperature profile to estimate the performance of photovoltaic systems

Tetiaroa Insolation Data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.578	6.63
February	0.579	6.43
March	0.61	6.24
April	0.608	5.43
May	0.591	4.55
June	0.616	4.36
July	0.626	4.59
August	0.634	5.31
September	0.631	6.11
October	0.6	6.45
November	0.586	6.64
December	0.526	6.07

Modeled Tetiaroa Insolation

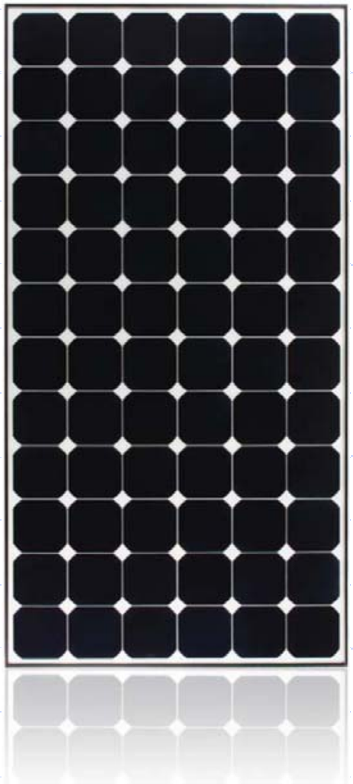


Photovoltaic System Assumptions

- The photovoltaic system was modeled using data from SunPower 215 panels. These panels are currently the most efficient available, the most responsive to obscured and oblique sunlight making them more tolerant in general, and come with a standard 25 year warranty

- SunPower 215 panel assumptions:
  - Temperature coefficient of power: -0.336 %/˚C
  - Normal operating cell temperature: 46˚C
  - Efficiency at std. test conditions: 16.7%
  - Derate factor*: 88%

- Each kW of installed photovoltaics (PV) takes an approximate area of 65 sqft.



Graphic of SunPower 215 Module

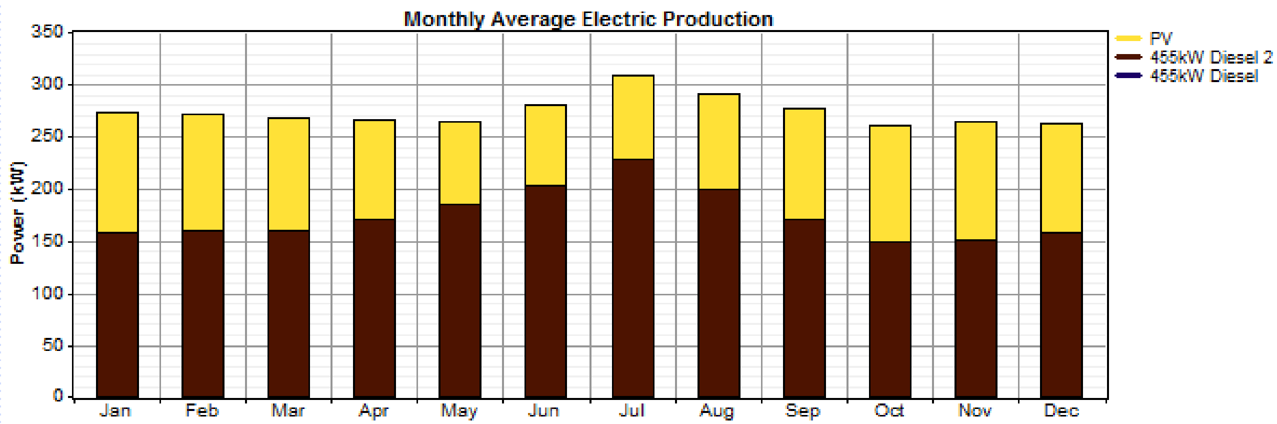
** The Derate Factor models panel output degradation due to age, shading, availability, soiling, AC & DC wiring, losses in diodes and connectors, etc.*

Photovoltaic System Assumptions

- System assumptions:
  - Capacity: 500 kW (DC)
  - Ground-mounted, slope* = 0˚

** Ideally, fixed-tilt PV systems should be mounted facing the sun at an angle of tilt equal to the site latitude. Tetiaroa is fairly close to the equator (latitude ~ 17˚), thus the effect of tilting the panels is relatively small – and results in only a 4% increase in annual energy production.*

- Model results (summary):
  - Annual production: 873,110 kWh
  - Average daily energy production: 2,392 kWh
  - Average power production: 100 kW
  - Potential island electrical demand met by PV: 42%



Monthy Electricity Demand met by PV vs. Diesel Gen Sets

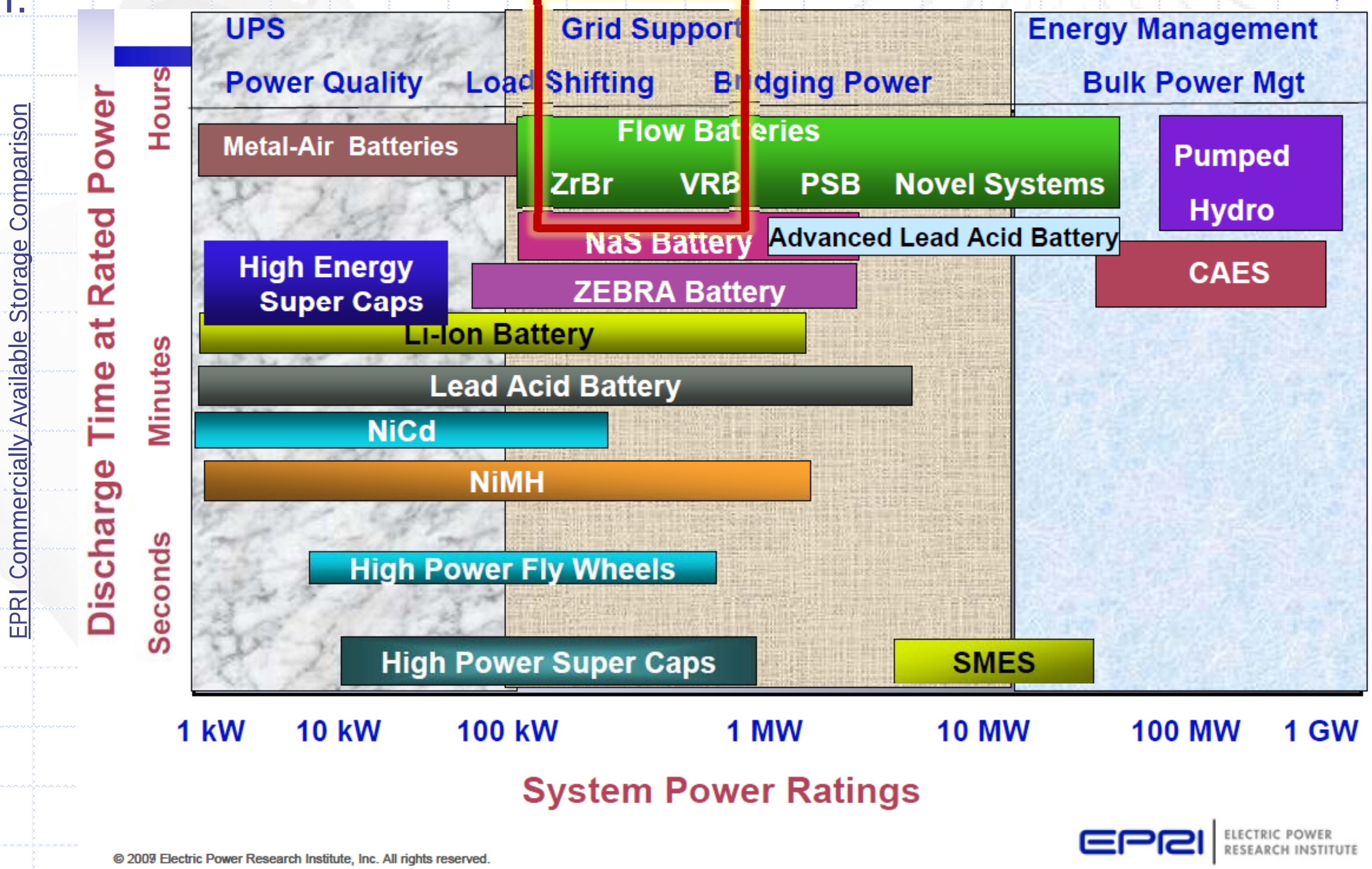
Energy Storage System

Energy Storage Design Goals

- The goal of this analysis was to suggest an alternative energy storage system to lead-acid batteries that provides:
  - Maintained power quality
  - Frequency and voltage (active and reactive power) regulation
  - System autonomy
  - Low # of diesel gen set starts & stops
  - Diesel-free operation at night (on average)
  - Maximized absorption of power produced from the PV array
  - Small footprint
  - Low O&M
  - Cost-effective
  - Long system life
  - Expandable solution

Energy Storage Solutions

- The resulting solution needs to be able to meet the island's peak power requirements for hours at a time. Thus, flow batteries present a viable solution:



Zinc Bromine Flow Battery

- How it works:
  - *A solution of zinc bromide is stored in two tanks. When the battery is charged or discharged the solutions (electrolytes) are pumped through a reactor stack and back into the tanks. One tank is used to store the electrolyte for the positive electrode reactions and the other for the negative.*
  - *The predominantly aqueous electrolyte is composed of zinc bromide salt dissolved in water. During charge, metallic zinc is plated from the electrolyte solution onto the negative electrode surfaces in the cell stacks. Bromide is converted to bromine at the positive electrode surface of the cell stack and is immediately stored in the electrolyte tank.*
  - *During charging zinc is electroplated onto conductive electrodes, while at the same time bromine is formed. On discharge the reverse process occurs, the metallic zinc plated on the negative electrodes dissolves in the electrolyte and is available to be plated again at the next charge cycle. In the fully discharged state, it can be left indefinitely for later charge.*

ZBB Energy

- The ZBB (zinc bromide battery) ZESS 500 presents a modular solution that meets the design requirements for Tetiaroa
- The ZESS 500 is a 500 kWh solution with 20+ year service design life
  - Easily transportable in containerized solution
  - Environmentally friendly – made from recyclable materials
  - High energy density relative to lead-acid batteries
  - 100% depth of discharge capability on a daily basis
  - No shelf life limitations
  - Scalable
  - Ability to store energy from any electricity generating source

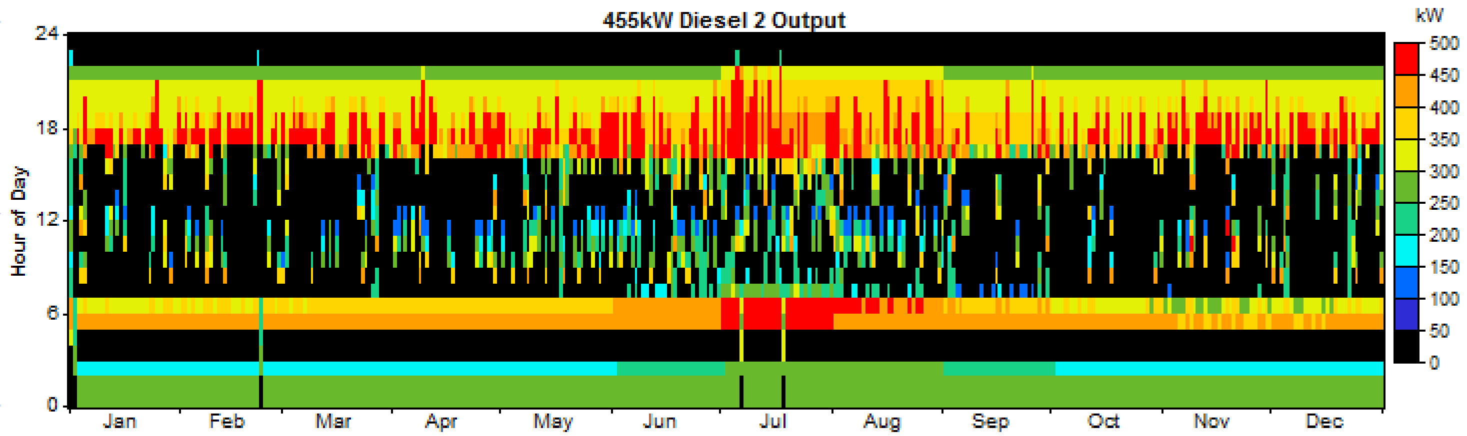
ZBB Energy modular ZESS500 solution

Battery System Sizing

- Each ZESS 500 consists of (10) ZESS 50 batteries. Each battery has a maximum discharge rate of 25kW. System designs were considered which varied between 10 and 30 batteries
- A model was created to show the behavior of the Load + Diesel gen set(s) + Battery as a microgrid system
- The effect of battery sizing on this microgrid system can be investigated by looking at the resulting diesel generator set usage pattern
- The mode requires a diesel generator set to run at any time step (t) where the following occurs:
  - (Load – PV Array Output– Operating Reserve) x t > Energy Stored

Battery System Sizing

- Example model 1: Battery size = 500kWh (one ZESS 500)

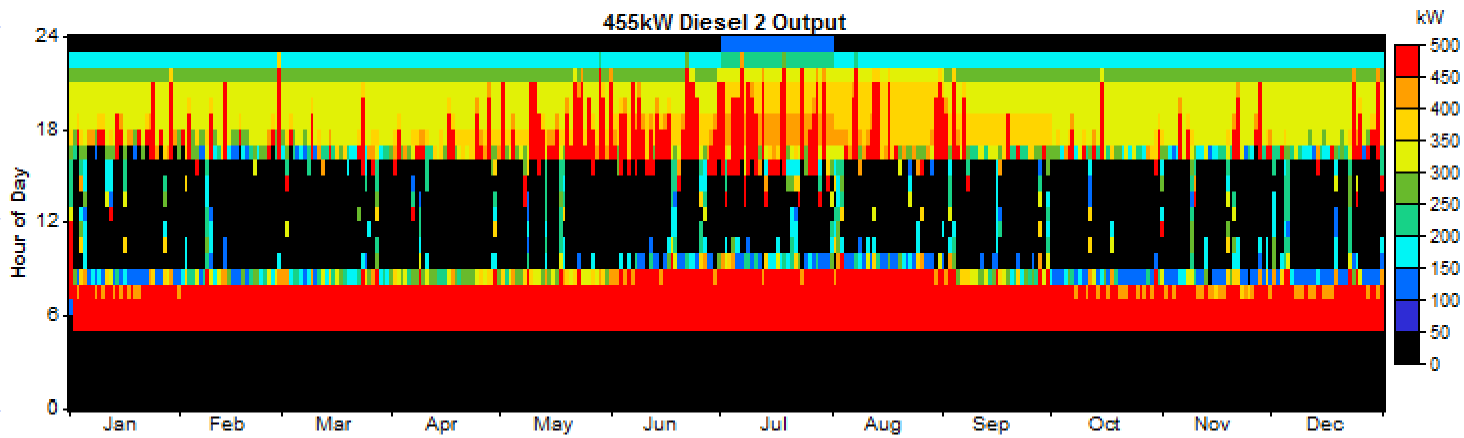


Modeled 455kW gen set output power

- Model Results:
  - The diesel generator set output varies wildly in the figure above. This is due to the fact that the generator set is frequently turning on & off to meet the demand
  - Estimated gen set performance: 1,252 starts / yr
  - Maximum discharge power of only 250kW
  - Battery sizing is too small to meet goals and will result in reduced gen set life

Battery System Sizing

- Example model 2: Battery size = 1000kWh (two ZESS 500)



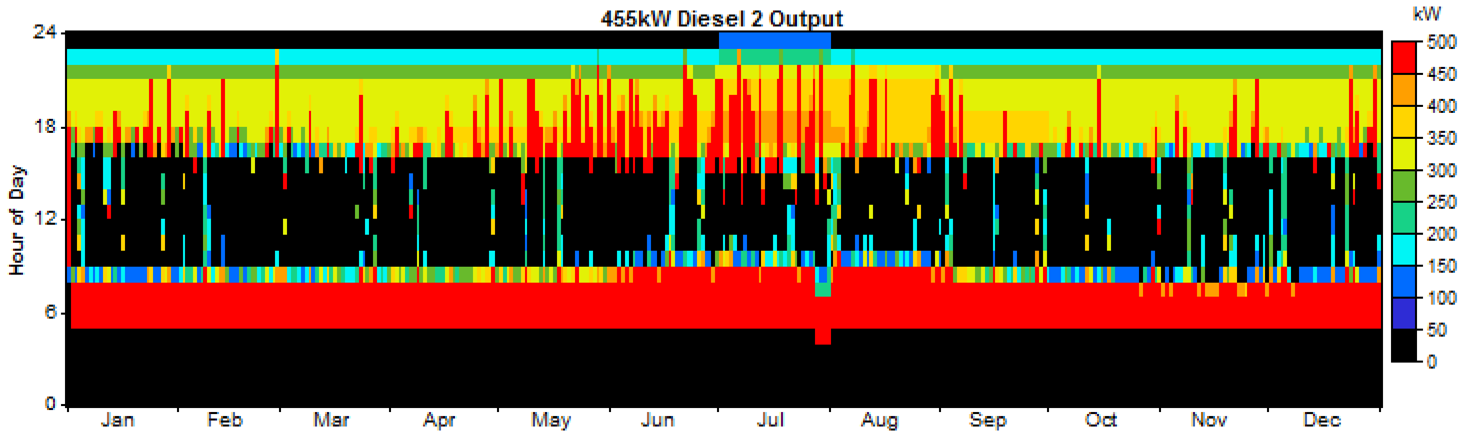
Modeled 455kW gen set output power

- Model Results:
  - The diesel generator set is not needed (on average) between:
    - 23:00 and 05:00
    - 09:00 and 16:00

    Thus, the battery is large enough to run the system autonomously at these times
  - Estimated gen set performance: 740 starts / yr
  - Maximum discharge power of 500kW (> maximum estimated load)

Battery System Sizing

- Example model 3: Battery size = 1500kWh (three ZESS 500)



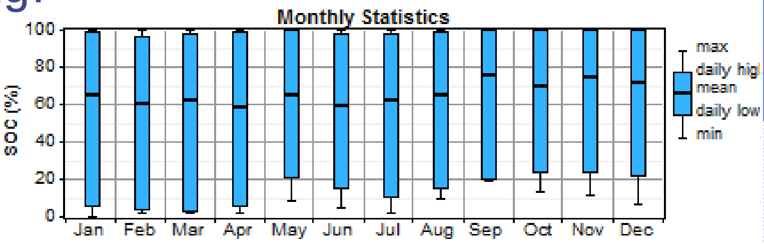
Modeled 455kW gen set output power

- Model Results:
  - The diesel generator set is not needed (on average) between:
    - 23:00 and 05:00
    - 09:00 and 16:00

    Thus, the battery is large enough to run the system autonomously at these times
  - Estimated gen set performance: 740 starts / yr
  - **Minor (if any) increase in performance over 1000kWh system**

Recommended System

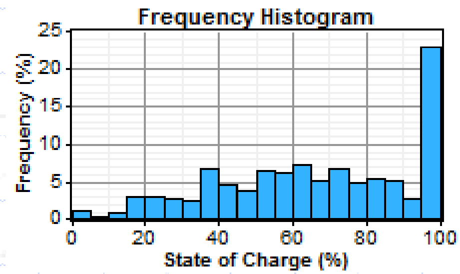
- (2) ZESS 500 energy storage units totaling:
  - 1000 kWh energy storage
  - 500 kW peak discharge power
  - 330 kW peak charge power



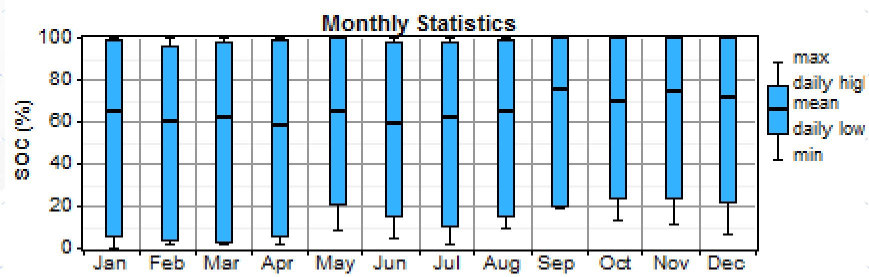
- ZBB POWR PECC (power electronic control center)
  - Connects generation sources, loads and batteries on a common 700 VDC buss
  - Generator sets are tied to DC buss via a rectifier
  - Generator set(s) told when to turn on/off (by POWR PECC) based on battery state of charge setpoints
  - PV array(s) tied to DC buss via DC/DC converter(s) with integrated MPPT control
  - Eliminates need for external PV inverters! (installed cost savings of ~ $250,000 USD)
  - Loads connected to DC buss through inverter(s) – creating smooth, controllable power quality

Recommended System

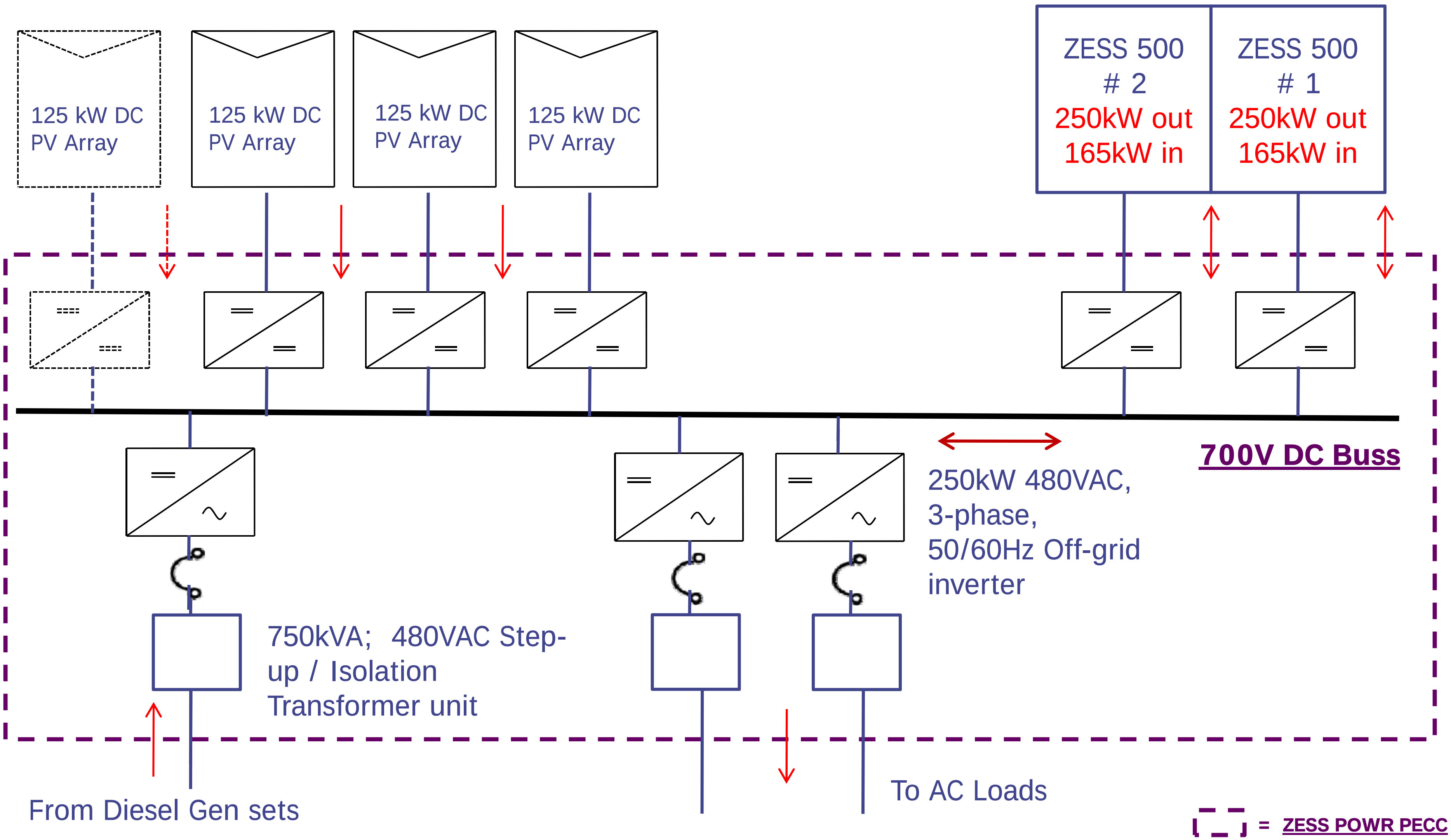
- Model results (summary):
  - Fuel use: 410,000 L/yr
  - CO_{2e} Emissions: 2,980 tonnes/yr



  - **30% reduction from hypothetical diesel-only system**
  - Operational lifetime of generator sets (assuming two identical generator sets, switched every 2-4 weeks): ~7yrs
  - Estimated system cost $1.625M USD



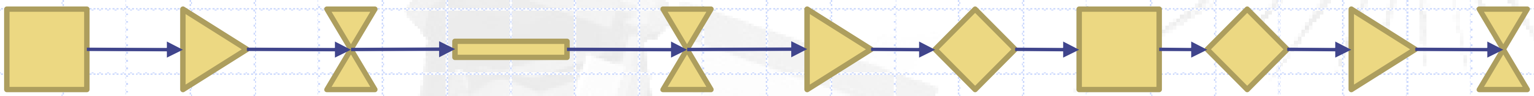
System Diagram



ZBB Round-Trip System Efficiency

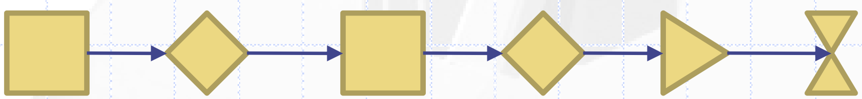
Contrast of dual grid-tie inverters versus DC-connected PV on the ZESS POWR™ PECC while moving energy from renewable generation to storage

Conventional Dual Grid-tie Inverters



PV	INV	TSFMR	AC LINE	TSFMR	INV	CONV	ZESS 500	CONV	INV	TSFMR	
1 kWHr	x 96% (-4%)	x 95.5% (-3.5%)	x 99% (-1%)	x 96.5% (-3.5%)	x 96% (-4%)	x 98% (-2%)	x 75% (-25%)	x 98% (-2%)	x 96% (-4%)	x 96.5% (-3.5%)	= 0.56kWHr

ZESS POWR PECC with DC-connected PV and a Shared Inverter



PV	CONV	ZESS 500	CONV	INV	TSFMR	
1 kW	x 98% (-2%)	x 75% (-25%)	x 98% (-2%)	x 96% (-4%)	x 96.5% (-3.5%)	= 0.67kWHr

Note 1: Aux Power not included for module control power, communications, pump motors and electrolyte chiller
(Chiller and pump motors only operate during Charge / Discharge resulting in varied load loss)
Note 2: High-efficiency (E3-type) transformers available; Efficiency improves to -1.4% loss

Estimated System Lifetime

- ZESS 50(kWH) module = 100,000 to 125,000kWH of 'discharge service life' on the cell stacks
  - 2000 events x 50kWh each = 100,000 'discharge' kWh before cell stack replacement
    - 2000 / 365 ~ 5.5 years
    - CAPEX of $xxx / 100,000kWH = $ cost / kWh used (not of $/kWH capacity; more like a statement on the cost per 'kW' for a generator)
    - This CAPEX cost per Discharge kWH goes down for overall kWH with each replacement of the cell stacks (it goes up with lead acid!)
  - 2500 event x 50kWH each = 125,000 'discharge' kWh
    - 2500 / 365 ~ 6.8 years

- The cell stack replacement is not a 'failure mode' but rather a 'degradation' of the round-trip efficiency of the cell stacks
  - Starting efficiency of present design = 72-75% (at the DC terminals, does not include 'system losses' at the DC/DC converters, AC/DC inverters, system transformer
  - Projected degradation with 'typical' use/year = 1 – 1.5%
  - Projected R-T efficiency in 5 years = 66 to 68% (less system losses (1-way) of ~ 8%; net of <60%
    - This threshold is seen as the 'tipping point' where efficiency losses start to outweigh the economic benefits of the overall power system performance

Additional ZBB-Supplied Materials

- ZBB Corporate Brochure (pdf)
- ZBB Standard Terms & Conditions (pdf)
- Operations and Maintenance Summary (pdf)
- ZESS 500 Charge / Discharge Curves (pdf)
- ZESS 500 Civil Works Requirements (pdf)
- ZBB POWR PECC Brochure (pdf)
- ZBB System Data Collection (pdf)

- ZBB vs. Lead Acid / 20 yr O&M Projection (xls)

- ZESS Island Power System Example (ppt)
- Tetiaroa Budgetary Proposal – Line Diagrams (ppt)

- Tetiaroa Budgetary Proposal (doc)