18-Design Approaches

Off-Grid Electrical Systems in Developing Countries

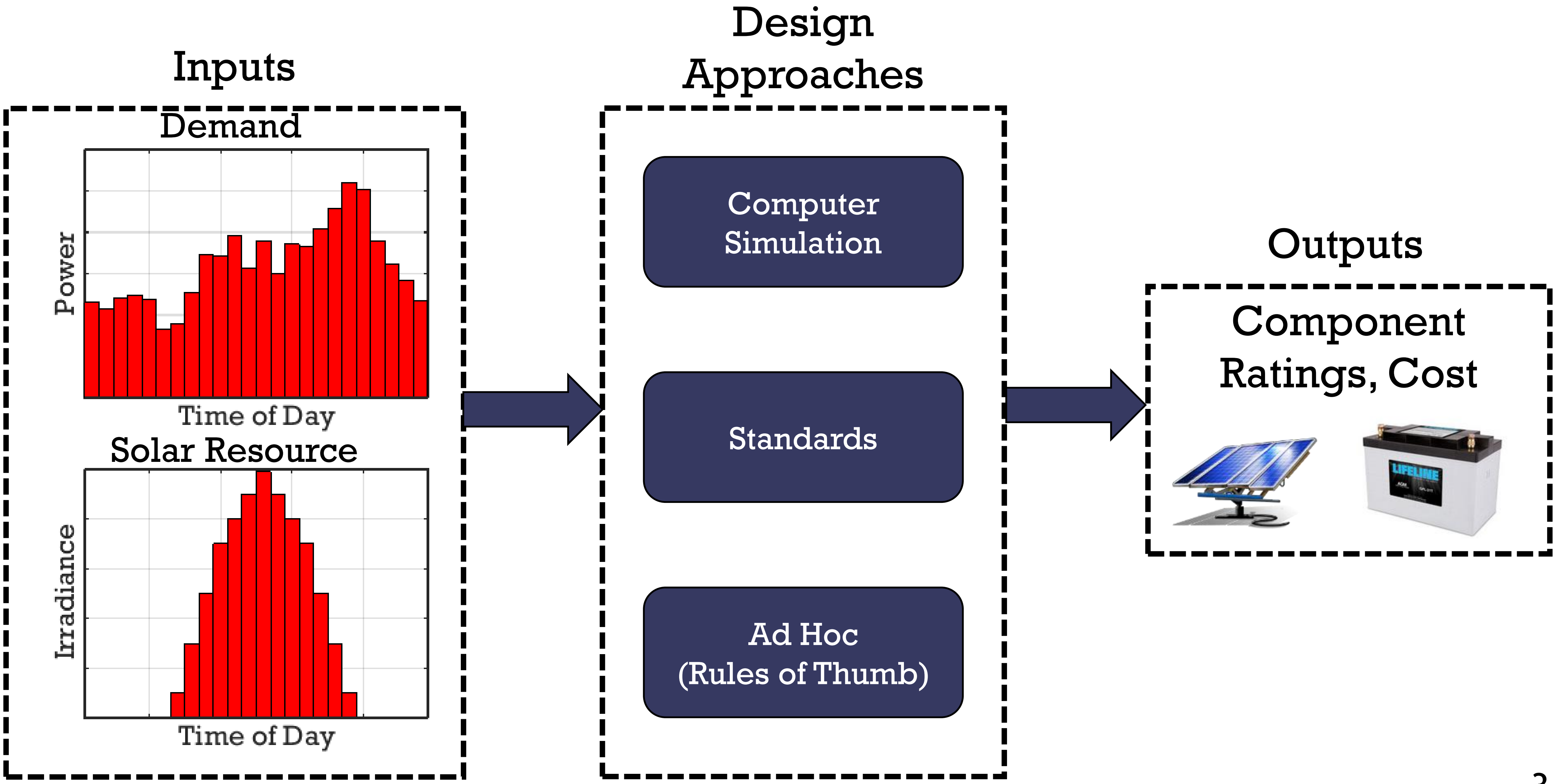
Chapter 12.4-12.6

Learning Outcomes

At the end of this lecture, you will be able to:

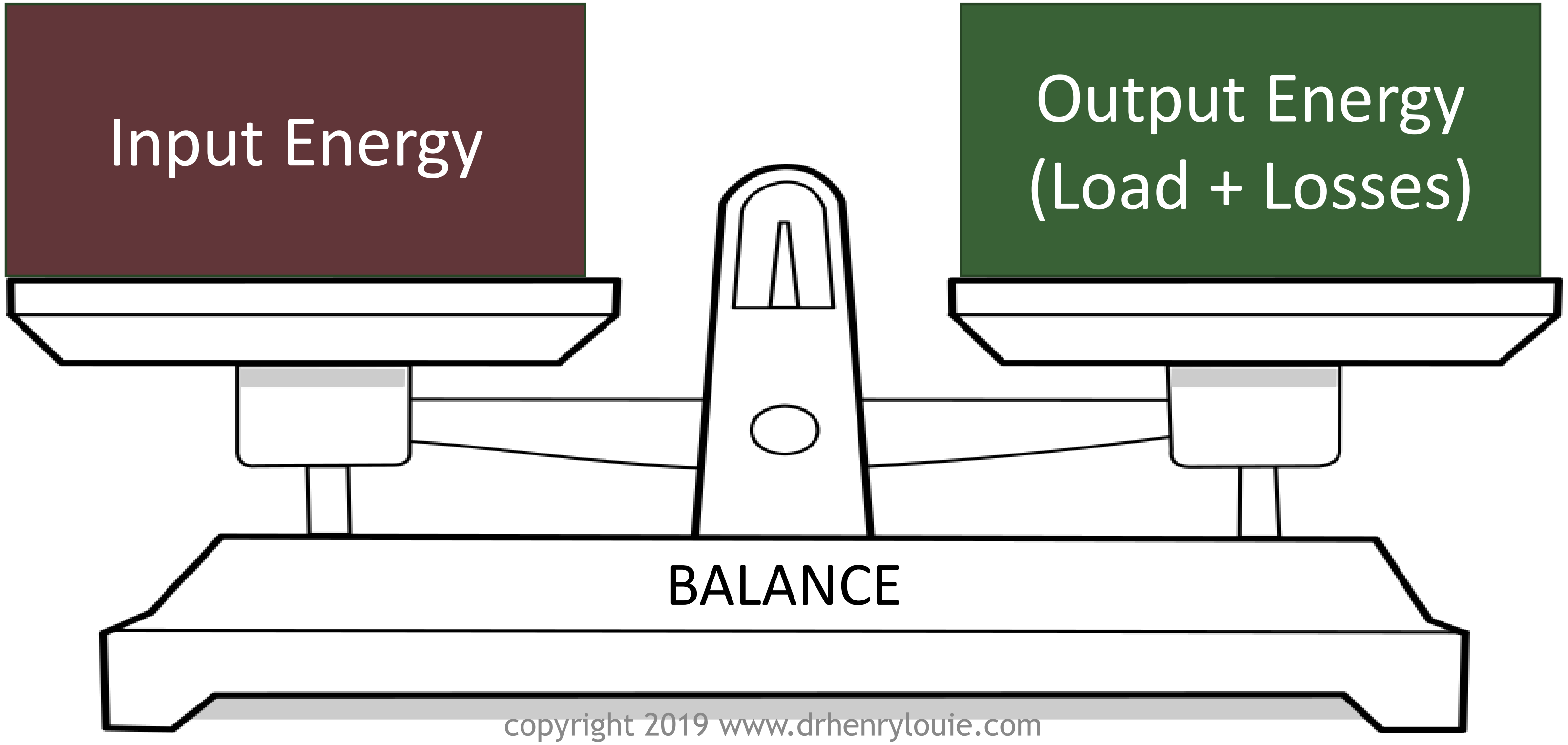
- ✓describe the numerical and intuitive approaches to off-grid system design
- ✓use a simple intuitive method to design an off-grid solar system
- ✓select appropriate battery, inverter, PV module, and charge controller based on their technical specifications

copyright 2019 www.drhenrylouie.com


Inputs
Demand
Power
Time of Day
Solar Resource
Irradiance
Time of Day
Design Approaches
Computer Simulation
Standards
Ad Hoc (Rules of Thumb)
Outputs
Component Ratings, Cost
LIFELINE

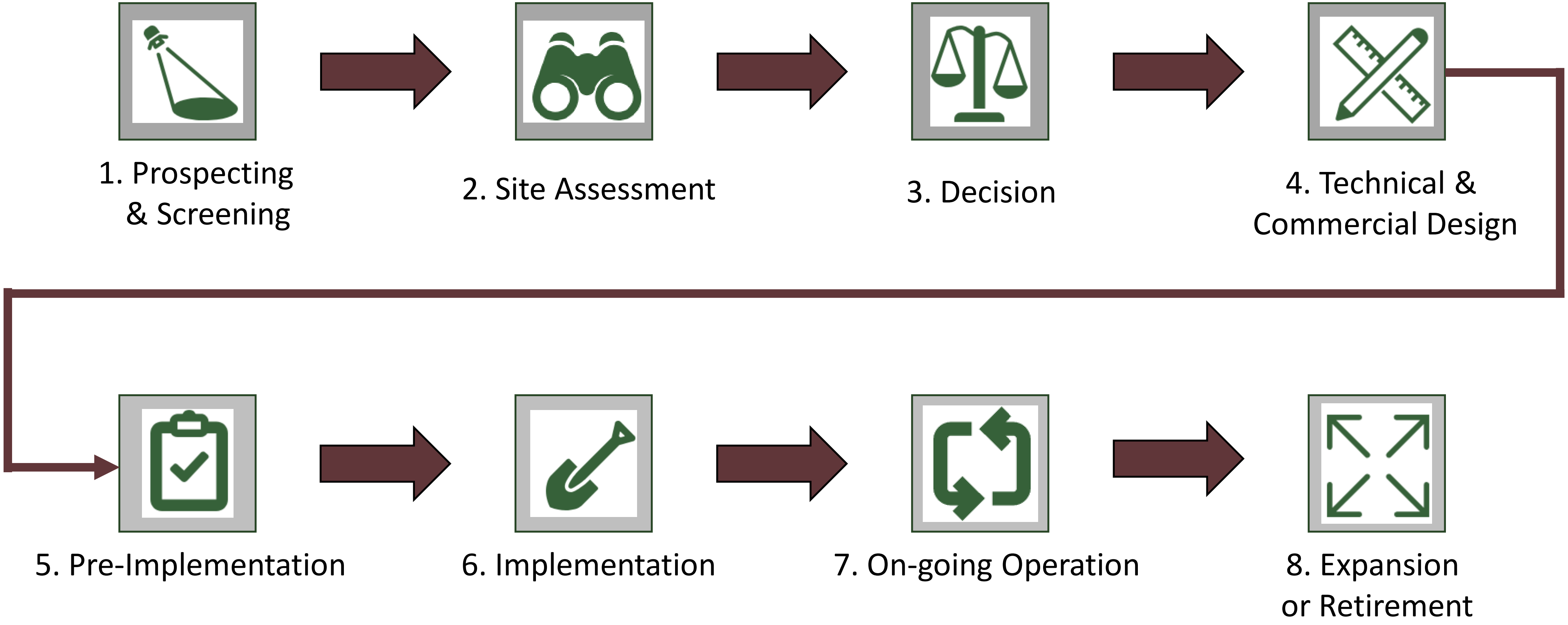
A technically-appropriate design is one that…

strikes a reasonable balance between the <u>cost</u> of implementing and operating the system with the ability of the system to <u>reliably</u> and safely meet the needs of its users



copyright 2019 www.drhenrylouie.com

Off-Grid System Life Cycle



copyright 2019 www.drhenrylouie.com

Design Approaches

Intuitive

Design by standards, guidelines or rules-of-thumb to size system components

Numerical

Design/analysis through computer-aided simulation

copyright 2019 www.drhenrylouie.com

Numerical Design

Designer

Technical and economic parameters of the system (system architecture, component sizing, energy resource characteristics, load, fuel cost)

Design Program

Hourly deterministic simulation of the system

Results

Technical and economic performance (capital expense, operating expense, cash flow, Levelized Cost of Energy)

copyright 2019 www.drhenrylouie.com

Numerical Design

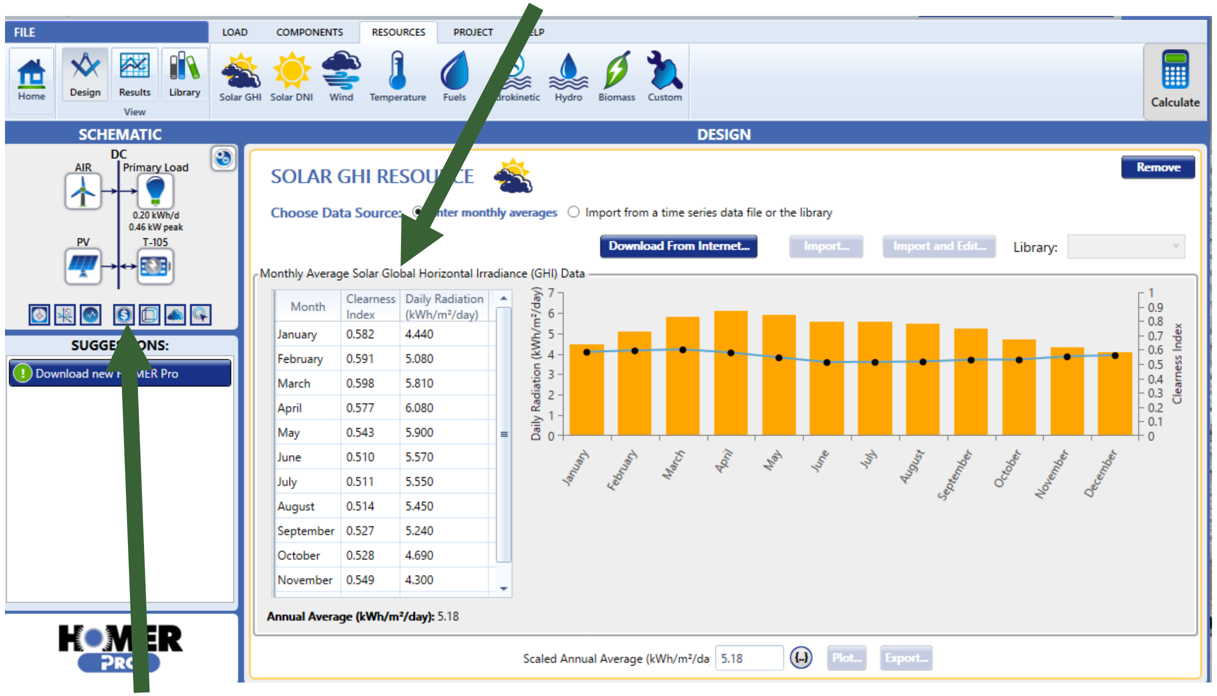
- Particularly useful for hybrid systems and those with complex control
- Allows for cost/reliability trade-offs of different designs to be recognized
- Input data requirements are high
- Results are only as good as the input information

"garbage in, garbage out"

copyright 2019 www.drhenrylouie.com

Example: HOMER

Resource Input



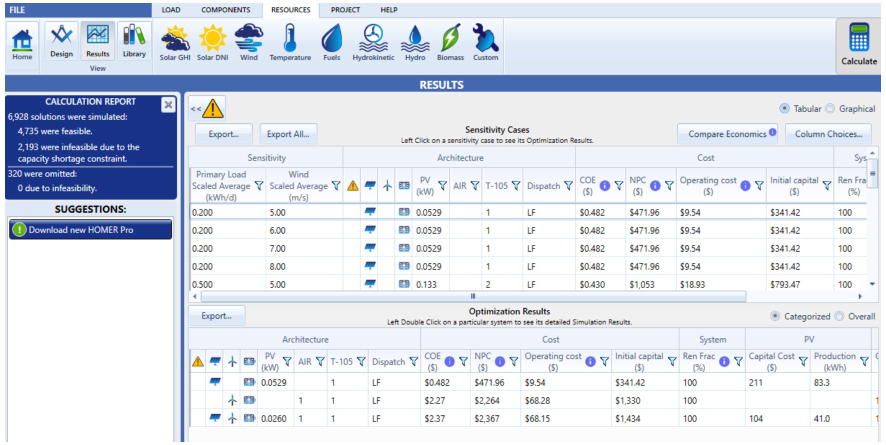
System Architecture

(courtesy Homer Energy)

Simulation Results

(courtesy Homer Energy)

Optimization Results



(courtesy Homer Energy)

copyright 2019 www.drhenrylouie.com

Intuitive Design

- Related standards
  - IEEE 1546.4: Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
  - IEEE 1526: Testing the Performance of Stand-Alone Photovoltaic Systems
  - IEEE 1013: Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems
  - IEC TS 62257: Recommendations for renewable energy and hybrid systems for rural electrification
  - Others under development (e.g. for DC mini-grids)
- Several other guidelines developed by various organizations

copyright 2019 www.drhenrylouie.com

Intuitive Design Example: Mwase

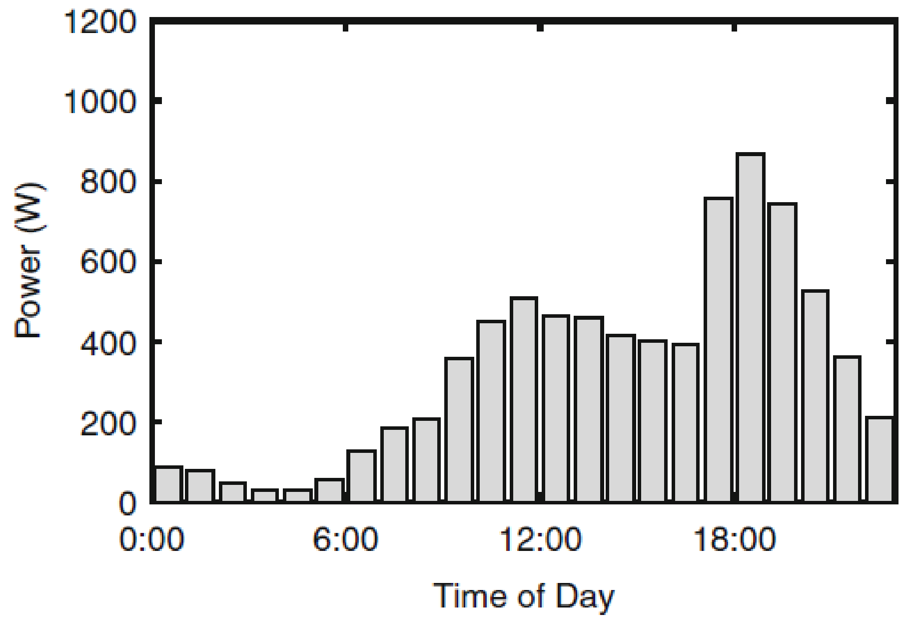
Basic Demographic Information

- Population 3000
- Nearest electrified town: 23 km away
- Road not well maintained, impassable during rainy season (November to February)
- Income sources: fishing, livestock, and farming
- Electrification needs: mix of 24 households, businesses, and a school
- Single phase 230VAC at 50Hz
- No acceptable WECS, MHP or biomass resources
- Design to accommodate 5 years of growth

copyright 2019 www.drhenrylouie.com

Load Estimation & Characterization

- Survey method used to produce load profile
  - Individual loads are aggregated into single load profile
  - Assumed weekday is the same as weekend
- Load growth estimate: 5% per year



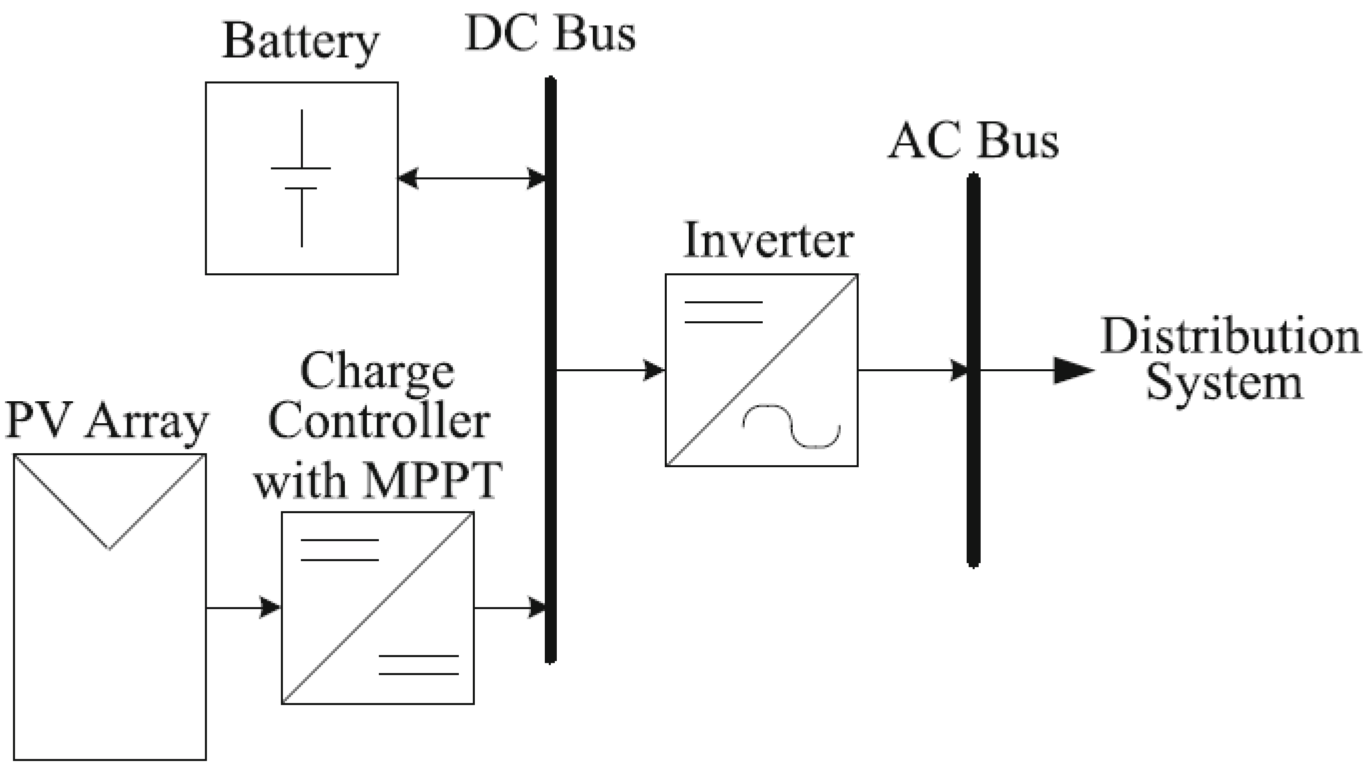
Parameter	Initial	After five years
Avg. daily load (kWh/day)	7.875	10.05
Peak individual load (kW)	4.11	5.24
Coincidence factor	0.37	0.37
Peak aggregate load (kW)	1.52	1.94
Power factor	0.85	0.85

copyright 2019 www.drhenrylouie.com

Sketch the Architecture of the System

copyright 2019 www.drhenrylouie.com

Architecture Selection



copyright 2019 www.drhenrylouie.com

Voltage Level Selection

Rule-of-thumb based on average daily load

Avg. Daily Load	DC Bus Voltage Level
<1 kWh	12V
1-4 kWh	24V
> 4 kWh	48V
>>4 kWh	96V or greater

Lower voltage requires higher current (more expensive cables) and more strings of batteries (but not necessarily more total batteries). Higher voltage increases the minimum number of batteries and has safety implications

copyright 2019 www.drhenrylouie.com

Inverter Selection

- Inverter must be capable of supplying peak load
- Include Design Margin to account for
  - elevated temperature operation
  - error in peak load estimate
- Many inverters rated in VA (adjust by assumed load power factor and temperature)

Inverter Power Requirement = Peak Load x (1 + Design Margin)

copyright 2019 www.drhenrylouie.com

Inverter Selection

- Mwase conditions
  - Peak Load: 1.94 kW
  - Power Factor: 0.85
  - High ambient temperature
- Use Design Margin of 0.20

$$\text{Inverter Power Requirement} = \text{Peak Load} \times (1 + \text{Design Margin})$$

$$\text{Inverter Power Requirement} = 1.94 \times (1 + 0.20) = 2.33 \text{ kW}$$

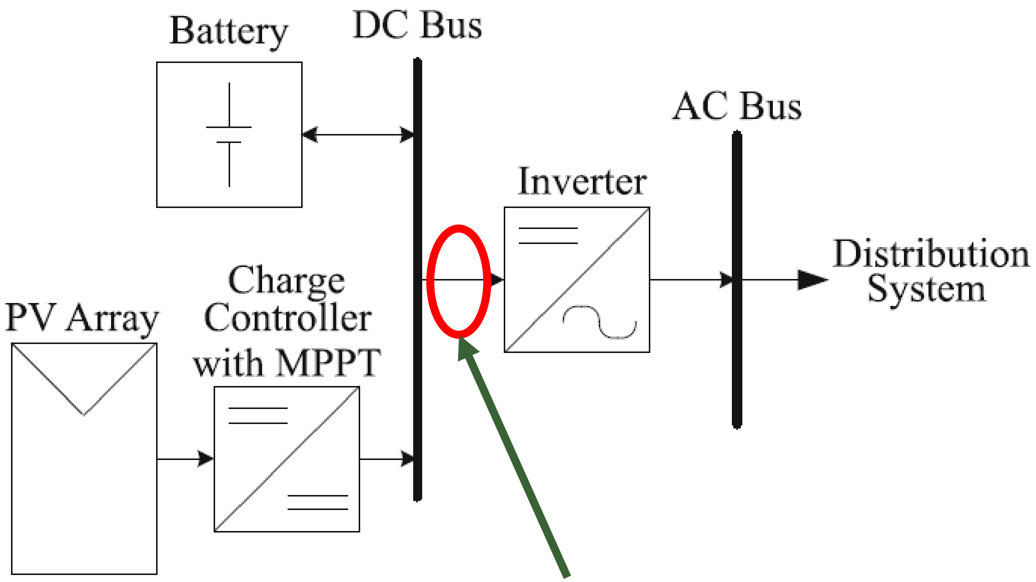
copyright 2019 www.drhenrylouie.com

Maximum Inverter DC Current

Needed as input to battery design

$$\text{Max. Inverter DC Current} = \frac{\text{Required Inverter Power}}{\text{Nominal Battery Voltage x Inverter Efficiency}}$$

estimate from inverter efficiency curve and load profile



inverter DC current

copyright 2019 www.drhenrylouie.com

Maximum Inverter DC Current

Mwase maximum inverter DC current

$$\text{Max. Inverter DC Current} = \frac{\text{Required Inverter Power}}{\text{Nominal Battery Voltage x Inverter Efficiency}}$$

Assume efficiency is 85%

$$57.14\ \text{A} = \frac{2330}{48 \times 0.85}$$

round up to 58A

copyright 2019 www.drhenrylouie.com

Inverter Selection

- Inverter must be compatible with:
  - DC bus voltage
  - AC bus voltage and frequency
  - AC power (real and/or apparent) at expected ambient temperature
- Other considerations
  - Efficiency
  - Stand-by (no load) power consumption
  - Total Harmonic Distortion
  - Low Voltage Disconnect functionality
  - Ability to operate in parallel with other inverters or AC sources

copyright 2019 www.drhenrylouie.com

Average Battery Load

Express average daily load in terms of amphours

$$\text{Average Battery Load} = \frac{\text{Average Daily Load (in Wh)}}{\text{Inverter Efficiency x Nominal Battery Voltage}}$$

Mwase system:

$$\text{Average Battery Load} = \frac{10{,}047}{0.85 \times 48} = 246.25 \text{ Ah}$$

copyright 2019 www.drhenrylouie.com

Battery Bank Design

- Main design factors
  - DC bus nominal voltage
  - Discharge current
  - Required reliability
- Reliability indirectly expressed as “Days of Autonomy”

copyright 2019 www.drhenrylouie.com

Days of Autonomy

- Days of Autonomy: number of days the battery bank can supply the average daily load before being depleted, assuming the bank is not recharged
- Fewer Days of Autonomy: lower cost, lower reliability
- Common range: 2 to 12 days
  - Doubling Days of Autonomy does not double reliability

copyright 2019 www.drhenrylouie.com

Battery Bank Capacity

Battery bank must be able to supply the average daily load for the selected Days of Autonomy, even at the end of the considered 5-year period

$$C_x = \text{Days of Autonomy} \times \text{Average Battery Load} \times \frac{1}{\text{End of Life Rating}}$$

After 5 years, the battery bank capacity will have decreased due to aging and use

copyright 2019 www.drhenrylouie.com

Battery Bank Capacity

Mwase system:

$$C_x = \text{Days of Autonomy} \times \text{Average Battery Load} \times \frac{1}{\text{End of Life Rating}}$$

$$C_x = 2 \times 246.25 \times \frac{1}{0.80} = 615.63 \text{ Ah}$$

Use an EoL of 80%

copyright 2019 www.drhenrylouie.com

Discharge Current for Battery Bank Capacity

- Recall that battery capacity is dependent on the discharge current, which is assumed to be constant
- Discharge current in most off-grid systems is not constant
- Reasonable values:
  - Average discharge current
  - Peak discharge current (most conservative)

copyright 2019 www.drhenrylouie.com

Discharge Current for Battery Bank Capacity

- For the Mwase system, assume that the peak discharge current is selected for the battery capacity reference
- Battery bank capacity requirement:
  - Battery must be able to supply 615.63 Ah when discharged at a current of 58A (C-rate of 0.094, hour-rate of 10.61 hours)
- Possible to use 615.63 Ah as the capacity, but other factors can be considered as shown next

copyright 2019 www.drhenrylouie.com

Depth-of-Discharge Considerations

- Avoid discharging battery to 0% state-of-charge (100% depth-of-discharge) to prolong its life
- Select a maximum acceptable depth-of-discharge
  - Usually 50 to 80%
- Adjust the capacity to ensure after all days of autonomy are "used" there is still remaining capacity

$$C'_x = C_x \times \frac{1}{DoD_{max}}$$

Maximum depth-of-discharge

copyright 2019 www.drhenrylouie.com

Depth-of-Discharge Considerations

Mwase system

Select maximum depth-of-discharge of 80%

$$C'_{58} = C_{58} \times \frac{1}{0.80} = 769.49 \text{ Ah}$$

Subscript reminds us what discharge current the capacity is referenced to

copyright 2019 www.drhenrylouie.com

Daily Depth-of-Discharge

- Next check that daily depth-of-discharge allows the battery bank to last the desired number of years (cycles)
- Consult considered battery cycle life chart
- Compute daily depth-of-discharge when battery bank capacity is C'_x
  - If depth-of-discharge is greater than required for desired number of cycles, increase battery capacity

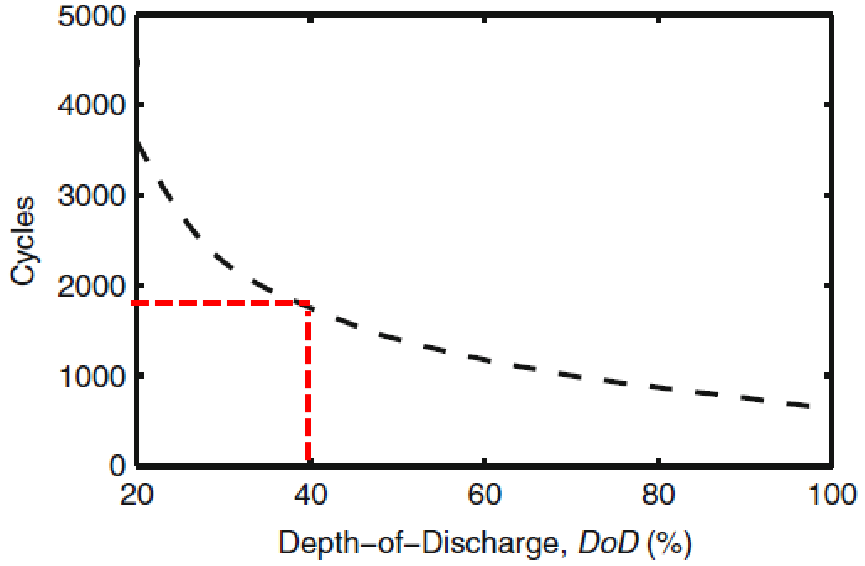
$$\text{Daily depth-of-discharge} = 100 \times \frac{\text{Avg. Daily Load}}{\text{Battery Bank Capacity}}$$

copyright 2019 www.drhenrylouie.com

Daily Depth-of-Discharge

Mwase system (AGM batteries)

- Cycle life target: 5 years (1825 cycles)
- Corresponding DoD: ~40%



Daily depth-of-discharge = $100 \times \frac{246.25}{769.49} = 32\%$

lower than 40%, so battery will last longer than 1825 cycles

copyright 2019 www.drhenrylouie.com

Battery Bank Design Margin

- Apply a design margin to account for
  - Load estimation error
  - Variability of daily load
  - Effects of temperature
  - Other losses

$$\text{Battery Bank Capacity} = C'_x \times (1 + \text{Design Margin})$$

copyright 2019 www.drhenrylouie.com

Battery Bank Design Margin

- Mwase system
  - Design margin of 7.5%

$$\text{Battery Bank Capacity} = C'_x \times (1 + \text{Design Margin})$$

$$\text{Battery Bank Capacity} = 769.49 \times (1 + 0.075) = 827.21 \text{ Ah}$$

Battery bank must have a capacity of 827.21 Ah
when discharged at 58A (C-rate of 0.07C, hour rate of 14.25 h)

copyright 2019 www.drhenrylouie.com

Battery Bank Configuration

Design the configuration of the battery bank

$$\text{Number of Series Batteries} = \frac{\text{Battery Bank Nominal Voltage}}{\text{Battery Nominal Voltage}}$$

$$\text{Number of Battery Bank Strings} = \frac{\text{Required Battery Bank Capacity}}{\text{Individual Battery Capacity}}$$

copyright 2019 www.drhenrylouie.com

Battery Bank Configuration

Assume battery considered has a 6V nominal voltage

$$\text{Number of Series Batteries} = \frac{\text{Battery Bank Nominal Voltage}}{\text{Battery Nominal Voltage}}$$

$$\text{Number of Series Batteries} = \frac{48}{6} = 8 \text{ batteries}$$

copyright 2019 www.drhenrylouie.com

Battery Bank Configuration

Use capacity based on 0.07C (14.25 h) rate

Hour-rate	10 hr (19A, 0.1C)	20 hr (11A, 0.05C)	48 hr (4.8A, 0.021C)	72 hr (2.96A, 0.014C)	100 hr (2.35A, 0.01C)
Capacity	190Ah	220Ah	228Ah	231Ah	235Ah

Hour rate of 14.25 not shown on table
Select a value somewhat above the 10 h rate, but below the 20 h rate
Use 200 Ah (or estimate using Peukert's Equation)

copyright 2019 www.drhenrylouie.com

Battery Bank Configuration

Hour-rate	10 hr (19A, 0.1C)	20 hr (11A, 0.05C)	48 hr (4.8A, 0.021C)	72 hr (2.96A, 0.014C)	100 hr (2.35A, 0.01C)
Capacity	190Ah	220Ah	228Ah	231Ah	235Ah

$$\text{Number of Battery Bank Strings} = \frac{\text{Required Battery Bank Capacity}}{\text{Individual Battery Capacity}}$$

$$\text{Number of Battery Bank Strings} = \frac{827.21\text{ Ah}}{200\text{ Ah}} = 4.13\text{ strings}$$

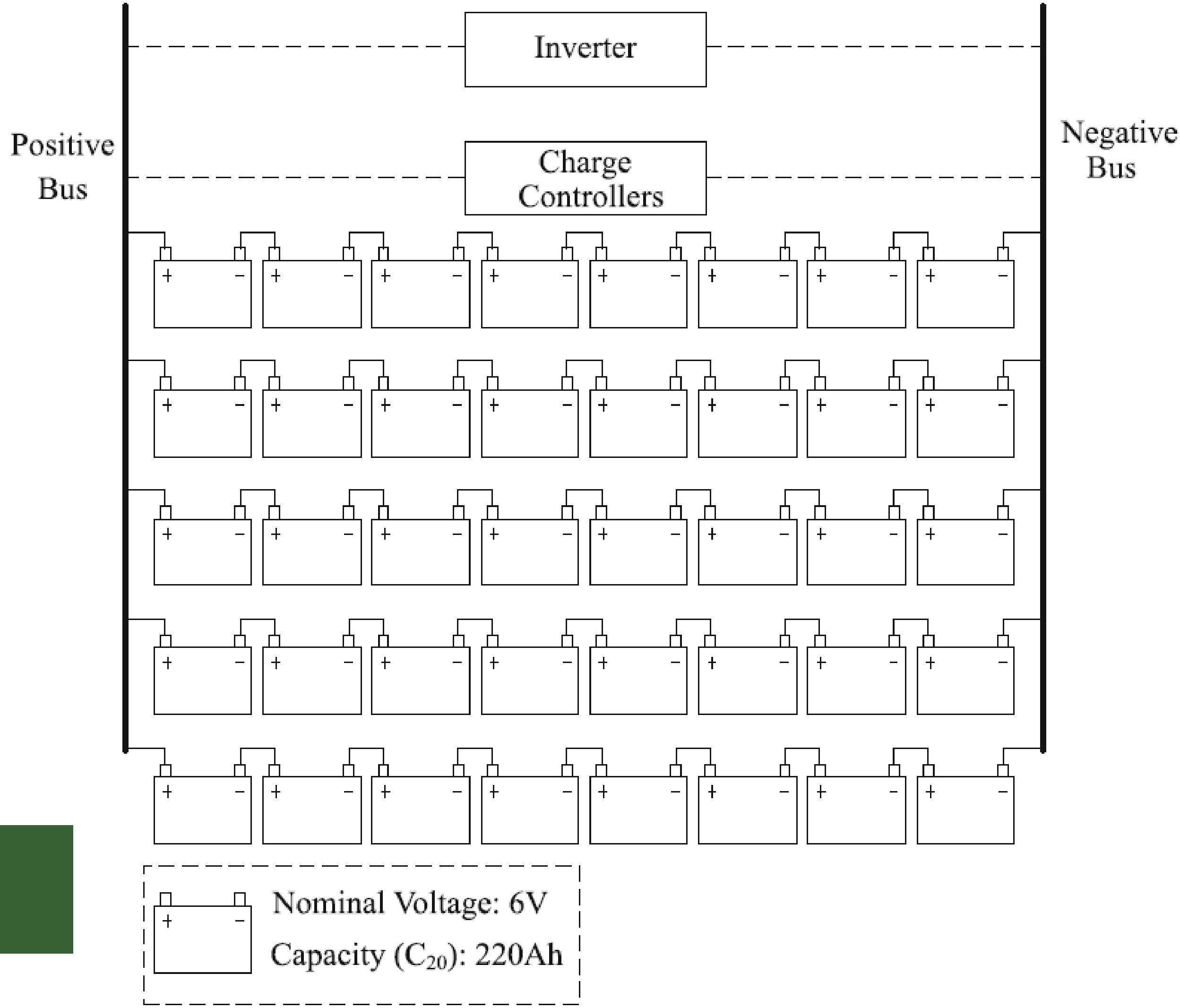
Round up to 5 strings

copyright 2019 www.drhenrylouie.com

Battery Bank Design

- Five strings of eight batteries
- Each string supplies 58/5 = 11.6A during peak load
- Design is conservative, four strings could likely be used
- Generally want to use as few strings as possible for safety reasons

Average daily load of 246.25 Ah resulted in a battery bank with capacity of 1100 Ah (220 x 5)



copyright 2019 www.drhenrylouie.com

Energy Source Design

- Energy source should be capable of supplying enough energy to supply the average load, accounting for generation and storage losses
- Design based on month with lowest resource availability
  - Dry season (MHP)
  - Winter/rainy season (PV)
  - Summer (WECS)
- If load is seasonal, consider extremes of load and resource

copyright 2019 www.drhenrylouie.com

PV Array Tilt

- Consult solar data base to determine expected insolation at various tilts
- Select tilt whose minimum insolation is the greatest

copyright 2019 www.drhenrylouie.com

Solar Resource

Average Daily Insolation (kWh/m^2/day)

Tilt	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Latitude -15°	5.51	5.61	5.69	5.76	5.36	**4.90**	5.15	5.99	6.51	6.78	6.19	5.54
Latitude	**5.08**	5.39	5.77	6.31	6.40	6.01	6.20	6.87	6.85	6.64	5.76	5.09
Latitude + 15°	4.47	4.94	5.54	6.46	6.89	6.58	6.78	7.23	6.76	6.15	5.08	**4.44**

Tilt PV array at Mwase's latitude (toward equator)

copyright 2019 www.drhenrylouie.com

Energy Source Design

- Average energy produced

$$\bar{E}_{PV} = P^{*}_{STC} \times \bar{I}$$

- Ignoring losses, PV array must be at least capable of suppling the average daily load with January's average daily insolation

$$P_{PV,rated} = \frac{\text{Average Daily Load (in kWh)}}{\text{Average Daily Insolation x Inverter Efficiency}} = \frac{10.05 \text{ kWh}}{5.08 \text{ kWh/m}^2\text{/day x } 0.85} = 2.33 \text{ kW}$$

copyright 2019 www.drhenrylouie.com

Generation & Storage Losses

- Array shading, including dust
- Wire and connection resistive losses
- Parasitic losses (stand-by consumption of controllers, monitors, data acquisition systems, and other devices)
- Module mismatch (caused by PV strings or modules having different maximum power points)
- Array degradation over time (aging)
- Throttled PV energy during battery charging absorption stage

copyright 2019 www.drhenrylouie.com

Accounting for Losses

- Losses are estimated based on local conditions
- Required PV array capacity increased by a total loss estimate K_L
- Mwase: $K_L = 22\%$

$$P'_{PV,rated} = \frac{P_{PV,rated}}{1 - K_L/100} = \frac{2.33}{1 - 0.22} = 2.98 \text{ kW}$$

Type	Low (%)	High (%)
Shading	0	40
Wire and connection loss	0	10
Parasitic loss	1	10
Module mismatch	0	5
Aging	0	15
Coulombic effect	5	25

copyright 2019 www.drhenrylouie.com

Temperature Effects

- PV production is decreased when cell temperature surpasses STC temperature (25^o C)
- Use historical temperature data during January to estimate cell temperature, and de-rate using power coefficient
  - Typically 2.5% to 17.5%
  - Mwase: 9.5%

$$P''_{PV,rated} = \frac{100 \times P'_{PV,rated}}{100 - \text{Temp. Reduction}} = \frac{100 \times 2.98}{100 - 9.5} = 3.29 \text{ kW}$$

copyright 2019 www.drhenrylouie.com

Design Margin

- Oversizing PV array can be considered to
  - increase reliability in case of consecutive overcast days
  - accommodate load growth
  - provide a buffer for load estimation error
- Apply design margin K_{PV}
  - Typically 10 to 20%
  - Mwase: 30% (rainy season)

$$P'''_{PV,rated} = \frac{P''_{PV,rated}}{1 - K_{PV}} = \frac{3.29}{1 - 0.3} = 4.71 \text{ kW}$$

copyright 2019 www.drhenrylouie.com

PV Array Design

- PV array for Mwase must have a capacity of at least 4.71 kW
- Begin by computing the minimum number of modules
- Assume PV modules have rated power of 350 W

$$\text{Number of Modules} = \frac{P'''_{PV,rated}}{\text{Module Rating}} = \frac{4.71\ \text{kW}}{0.35\ \text{kW}} = 13.46$$

Rounded up to 14

copyright 2019 www.drhenrylouie.com

Charge Controller Selection

- Charge controller must be compatible with:
    - DC bus voltage
    - PV array open-circuit voltage, short-circuit current, maximum power
    - DC power at expected ambient temperature
- Other considerations
    - Efficiency
    - Stand-by (no load) power consumption
    - Battery charging algorithms (three-stage for lead-acid battery)

copyright 2019 www.drhenrylouie.com

PV Array Design

- PV array layout constrained by charge controller maximum input voltage, current and power
- PV array capacity > 3500 W
  - Two charge controllers needed
- Open-circuit voltage limits number of modules per string
- Some charge controllers require the PV voltage to be larger than the battery bank voltage
- Short-circuit current limits number of strings per charge controller

Charge Controller Parameters	Value
Maximum power	3500 W
Maximum open-circuit voltage	150 V
Maximum short-circuit current	60 A
Maximum DC Bus Voltage (Nominal)	48 V

copyright 2019 www.drhenrylouie.com

PV Array Design Max. Modules per String

- Place as many modules in series as possible
- Maximum number of modules per string

PV Module Parameters	Value
Maximum power	350 W
Open-circuit voltage (STC)	47.43 V
Short-circuit current (STC)	9.49 A

$$\text{Max. Modules per string} = \frac{\text{Charge Controller Max Voltage}}{\text{PV Module Open-Circuit Voltage}} = \frac{150}{47.43} = 3.16$$

Round down to 3

Check to see if temperature-adjusted open-circuit voltage is less than maximum controller voltage

copyright 2019 www.drhenrylouie.com

PV Array Design Strings per Controller

- High irradiance increases short-circuit current from module
- Maximum number of strings per controller

PV Module Parameters	Value
Maximum power	350 W
Open-circuit voltage (STC)	47.43 V
Short-circuit current (STC)	9.49 A

$$\text{Max. Strings per Controller} = \frac{\text{Charge Controller Max Current}}{\text{PV Module Short-Circuit Current x 1.25}} = \frac{60}{11.86} = 5.06$$

Represents the case of irradiance at 1250 W/m^2

Round down to 5

copyright 2019 www.drhenrylouie.com

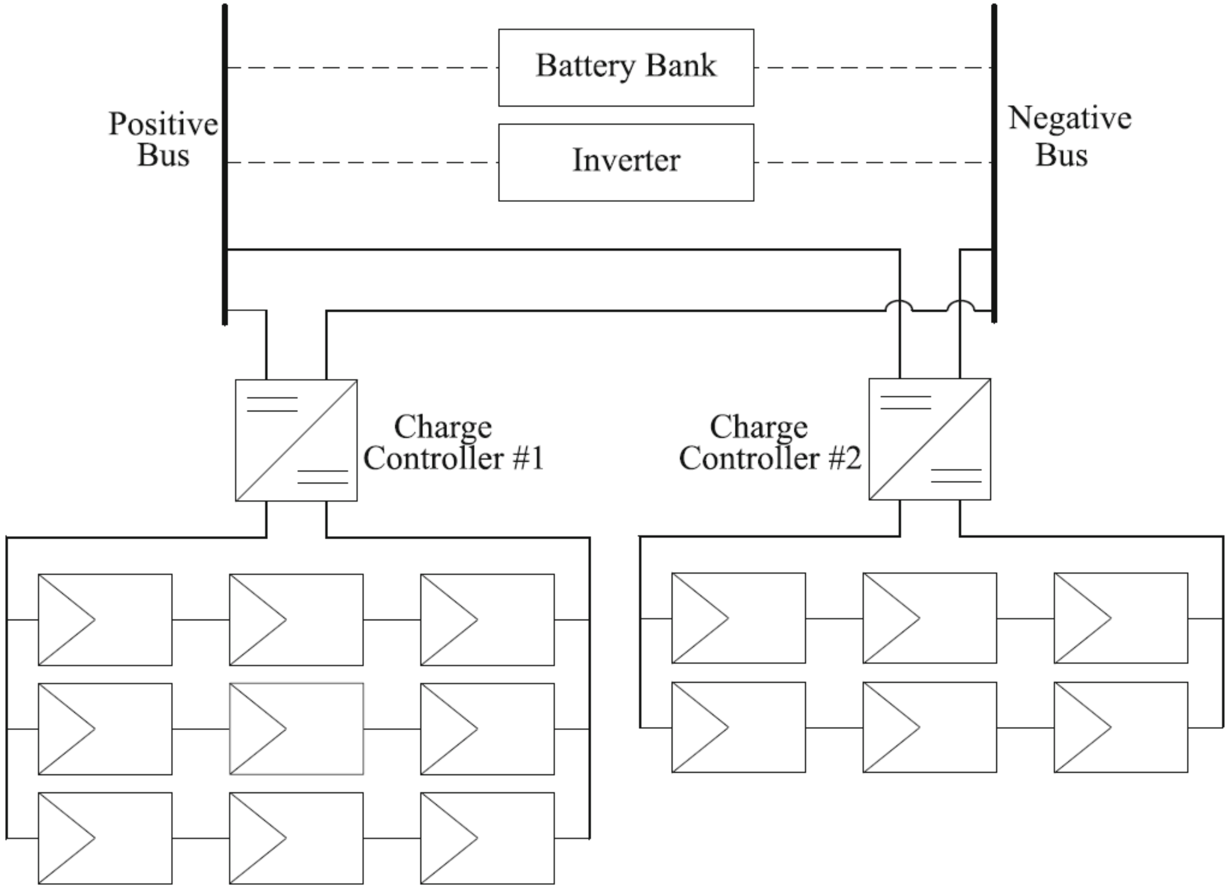
PV Array Design Constraints

- No more than 10 modules connected to each charge controller (power rating of 3500 W)
- Number of modules per string must be the same, and cannot exceed 3
  - Possible for each charge controller to have different number of series connected modules
- Number of strings per controller cannot exceed 5
- Number of modules must be at least 14

copyright 2019 www.drhenrylouie.com

PV Array Layout

Several layouts possible



Cost Estimate

Table 12.12 Component cost

Item	Each (US$)	No.	Total (US$)
PV module (350 W)	580	15	8700
Battery (220Ah)	204	40	8160
Inverter (2.4kW)	1275	1	1275
Charge controller (150V/60A)	600	2	1200
		Total	US$19,335

Table 12.13 Other costs for Mwase

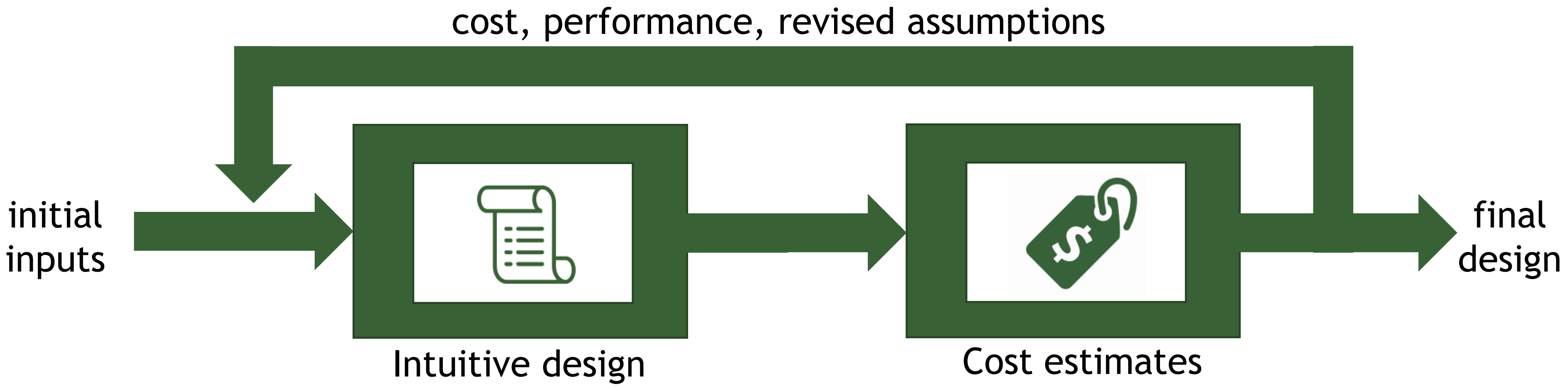
Item	Each (US$)	No.	Total (US$)
PV mounting rack	1200	1	1200
Battery monitor	290	1	290
Other BoS components	2000	1	2000
Installation (labor and travel)	1800	1	1800
Power house construction	2000	1	2000
		Total	US$7290

Compare estimated cost to budget, make Adjustments as necessary (e.g. change days of autonomy, connect more/less users, etc.)

copyright 2019 www.drhenrylouie.com

Iterative Design

- Developed design is a starting point
- Modified to reduce cost, increase reliability



copyright 2019 www.drhenrylouie.com

Contact Information

Henry Louie, PhD

Professor

Seattle University

@henrylouie

hlouie@ieee.org

Office: +1-206-398-4619