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Solar PV Off-Grid System Design: Foundations and AI Applications

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Oluleke Babayomi, PhD

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Henry Louie, PhD

Dr. Henry Louie is a Professor in the Department of Electrical and Computer Engineering at Seattle University.

In 2015 Dr. Louie was Fulbright Scholar to Copperbelt University in Kitwe, Zambia, and a Fulbright Specialist to the Zambian National Institute of Public Administration in 2025. He is the President and Co-founder of KiloWatts for Humanity, a non-profit organization providing off-grid electricity access and business opportunities in sub-Saharan Africa. Dr. Louie is an Associate Editor for *Energy for Sustainable Development* and is a founding member of the IEEE PES Working Group on Sustainable Energy Systems for Developing Communities.

Dr. Louie is recognized as an IEEE Distinguished Lecturer for his expertise on energy poverty. He is a Senior Member of the IEEE and has been a registered professional engineer in Zambia. He previously served as Vice President of Membership & Image of the IEEE Power & Energy Society. He is the past chair of the IEEE PES/IAS PowerAfrica Conference Steering Committee and previously served on the IEEE Smart Village Steering Committee. He is the recipient of the 2024 IEEE PES Peter W. Sauer Outstanding Power Engineering Educator Award.



www.kilowattsforhumanity.org

Oluleke Babayomi, PhD

Dr. Oluleke Babayomi is a Research Scientist and project lead on electrical grid modernization, digitalization and decarbonization at the Tyndall National Institute, Cork, Ireland. He previously held positions at Kumoh National Institute of Technology, South Korea and the Korea Advanced Institute of Science and Technology (KAIST). He received his Ph.D. in Electrical Engineering from Shandong University, China, and his Master's and Bachelor's (Hons) degrees from the University of Lagos, Nigeria.

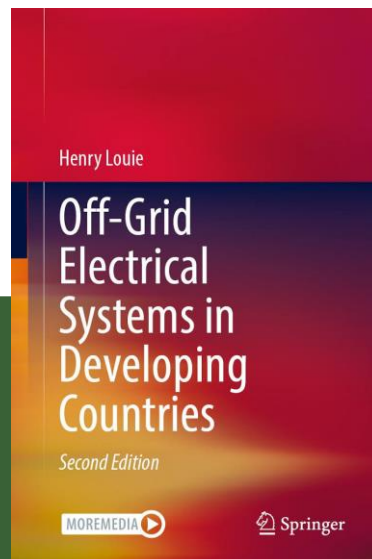


His research expertise spans trustworthy machine learning for sustainable energy, smart- and micro-grids, and the advanced control of power electronics. Dr. Babayomi has delivered multiple IEEE-sponsored tutorials and invited presentations, including tutorials at IEEE-IES ONCON 2023 at IEEE PRECEDE 2023. He serves as Guest Editor & Associate Editor for the IEEE Transactions on Power Electronics and is a recipient of the 2024 IEEE Power Electronics Society Ph.D. Thesis Talk Award and the 2024 IEEE Smart Village Leadership Award. He is a Senior Member of IEEE and a Fellow of the Nigerian Institute of Electrical and Electronic Engineers.

Tyndall

Table of Contents

- 1: Energy and Human Development
- 2: Energy Poverty
- 3: Grid Extension and Enhancement
- 4: Off-Grid System Architectures
- 5: Off-Grid Photovoltaic Arrays
- 6: Off-Grid Generators and Gen Sets
- 7: Off-Grid Biomass Systems
- 8: Off-Grid Wind Energy Conversion Systems
- 9: Off-Grid Micro Hydro Power Systems
- 10: Off-Grid Energy Storage Systems
- 11: Off-Grid System DC Converters and Rectifiers
- 12: Off-Grid System AC Converters and Inverters
- 13: Off-Grid System Battery Operation and Control
- 14: Off-Grid System Operation and Control
- 15: Off-Grid System Load and Energy Resource Estimation
- 16: Off-Grid Energy Production System Design
- 17: Off-Grid Distribution System Design
- 18: Solar Lanters and Solar Home Systems
- 19: Economic, Social, and Other Considerations



These slides available at:
drhenrylouie.com/pac



Additional slides available at:
<https://github.com/Off-Grid-Textbook>



Other information
drhenrylouie.com





Agenda: Session 1

Module A: Off-Grid Load & Resource Estimation (30 min.)

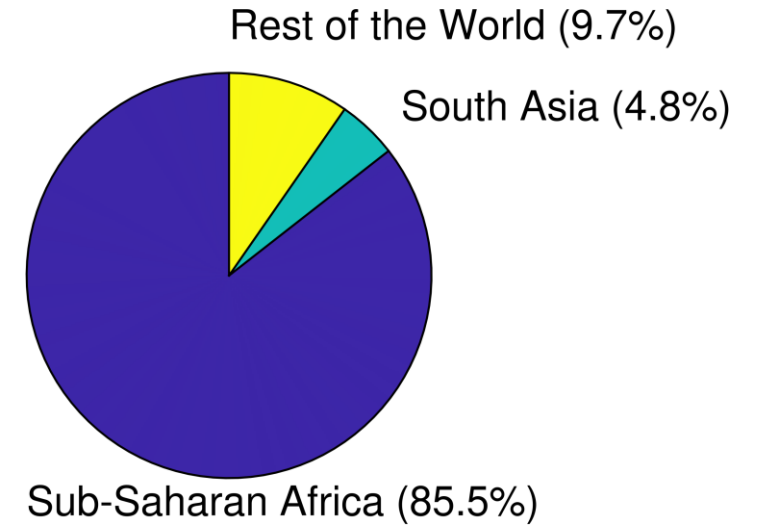
Module B: Off-Grid Energy Production System Design (60 min.)

Module C: Off-Grid Distribution System Design (20 min.)

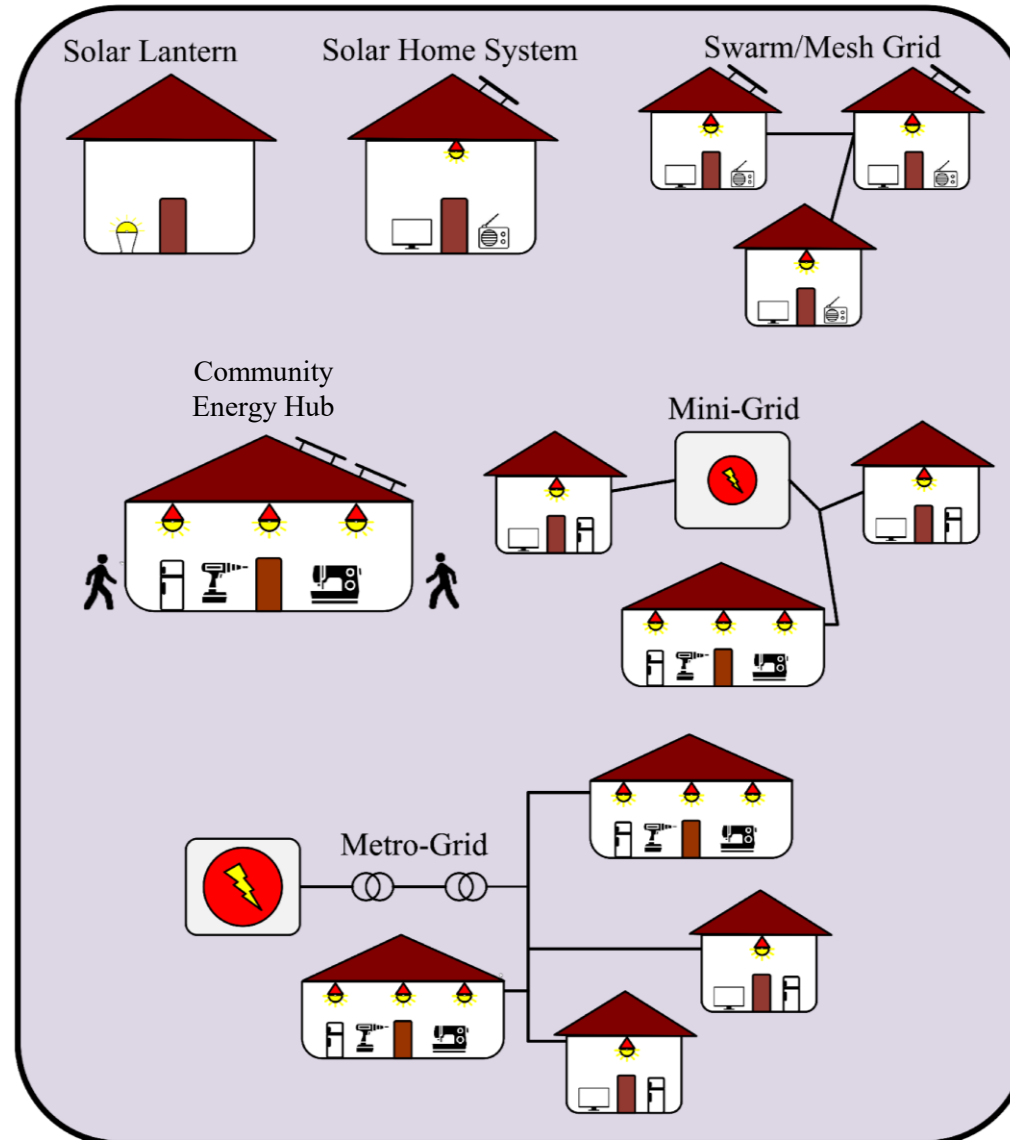
Module D: Bridge to AI Applications + Q&A

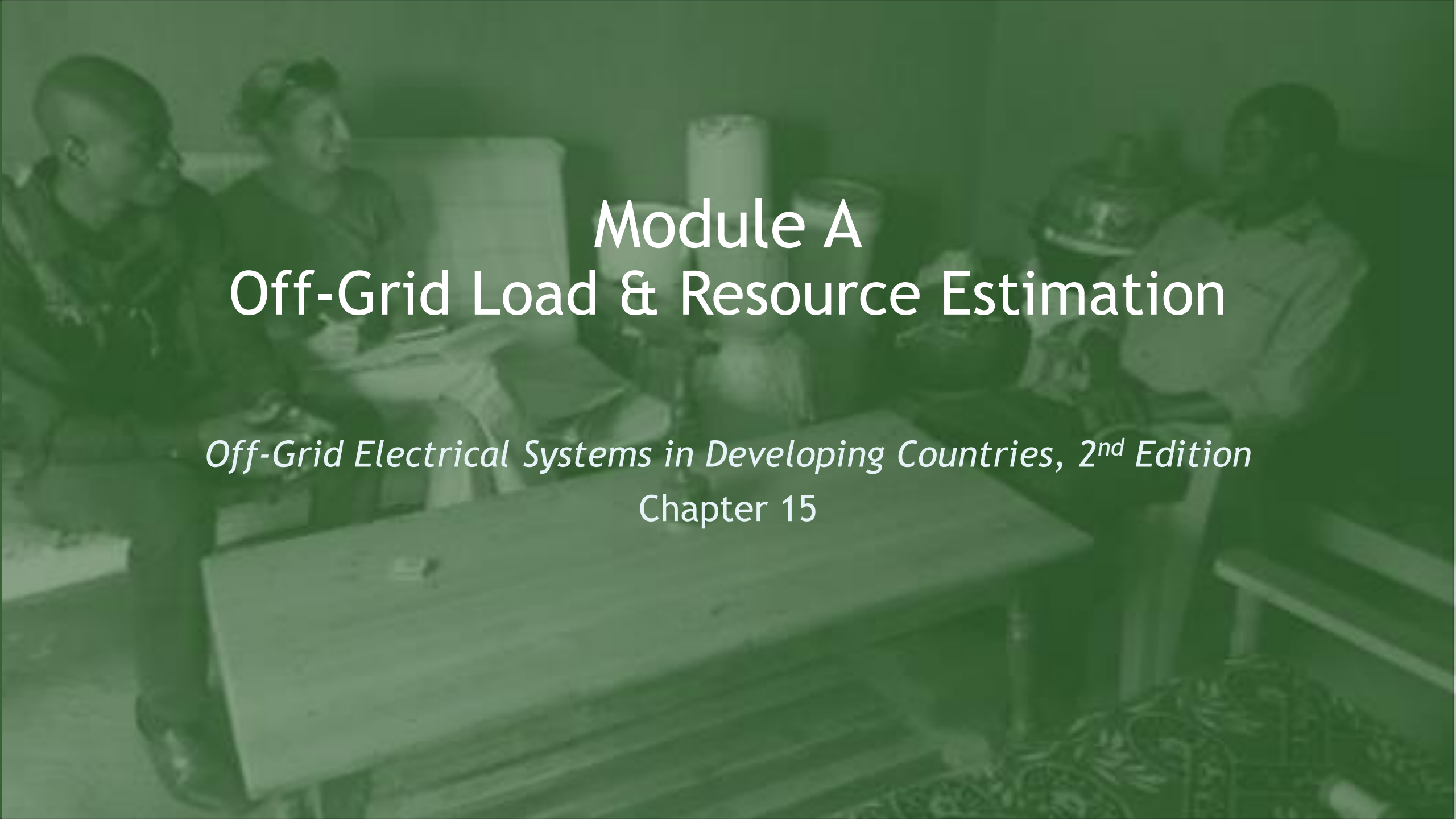
Electricity Access

- As of 2022, +685 million people without access to electricity in their home
- Majority live in Sub-Saharan Africa (SSA)



Electrification Approaches



A group of people are seated around a large wooden table in a meeting room. The image is overlaid with a semi-transparent green filter. The text is centered over the image.

Module A

Off-Grid Load & Resource Estimation

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 15



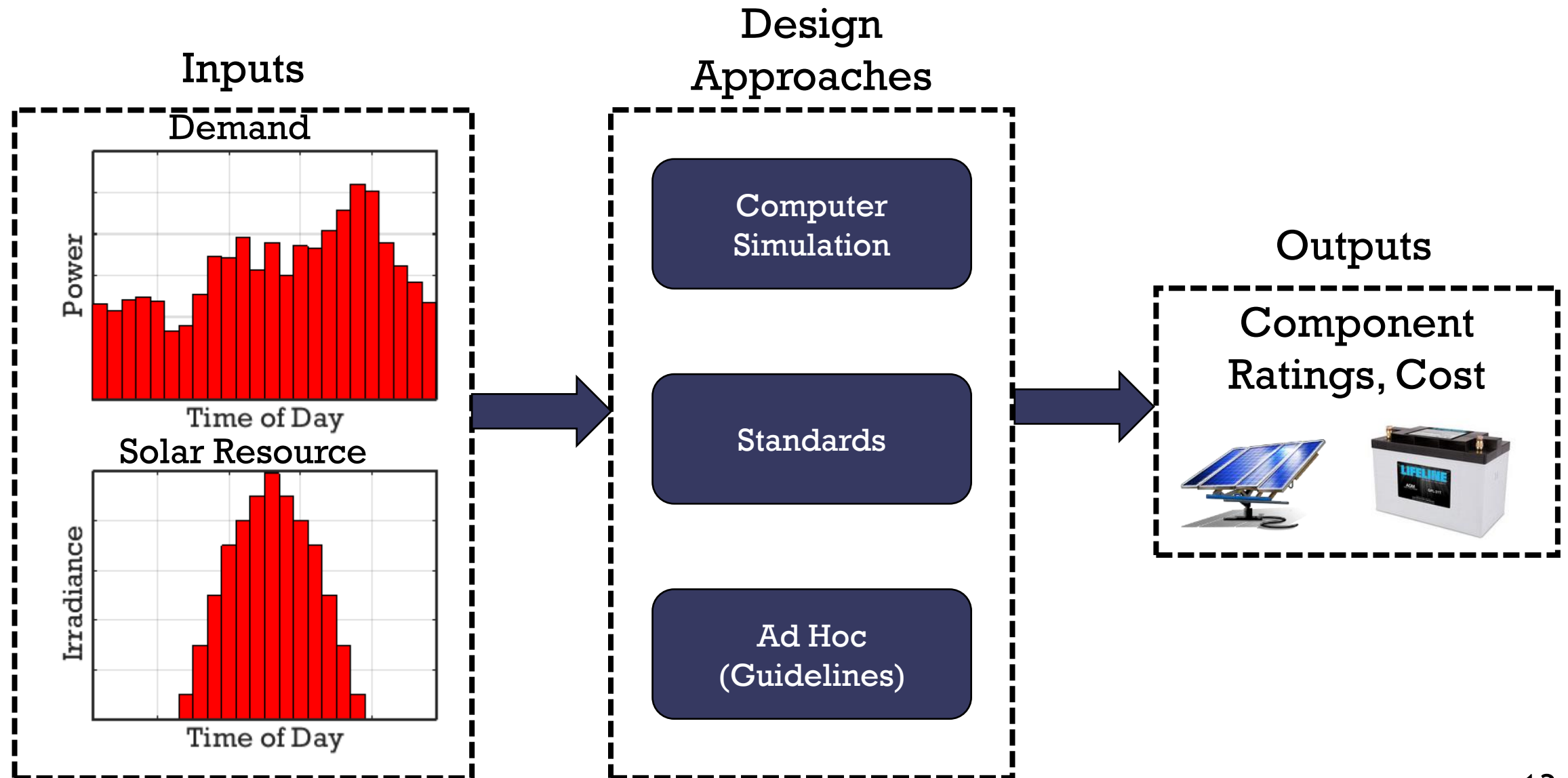
Learning Outcomes

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

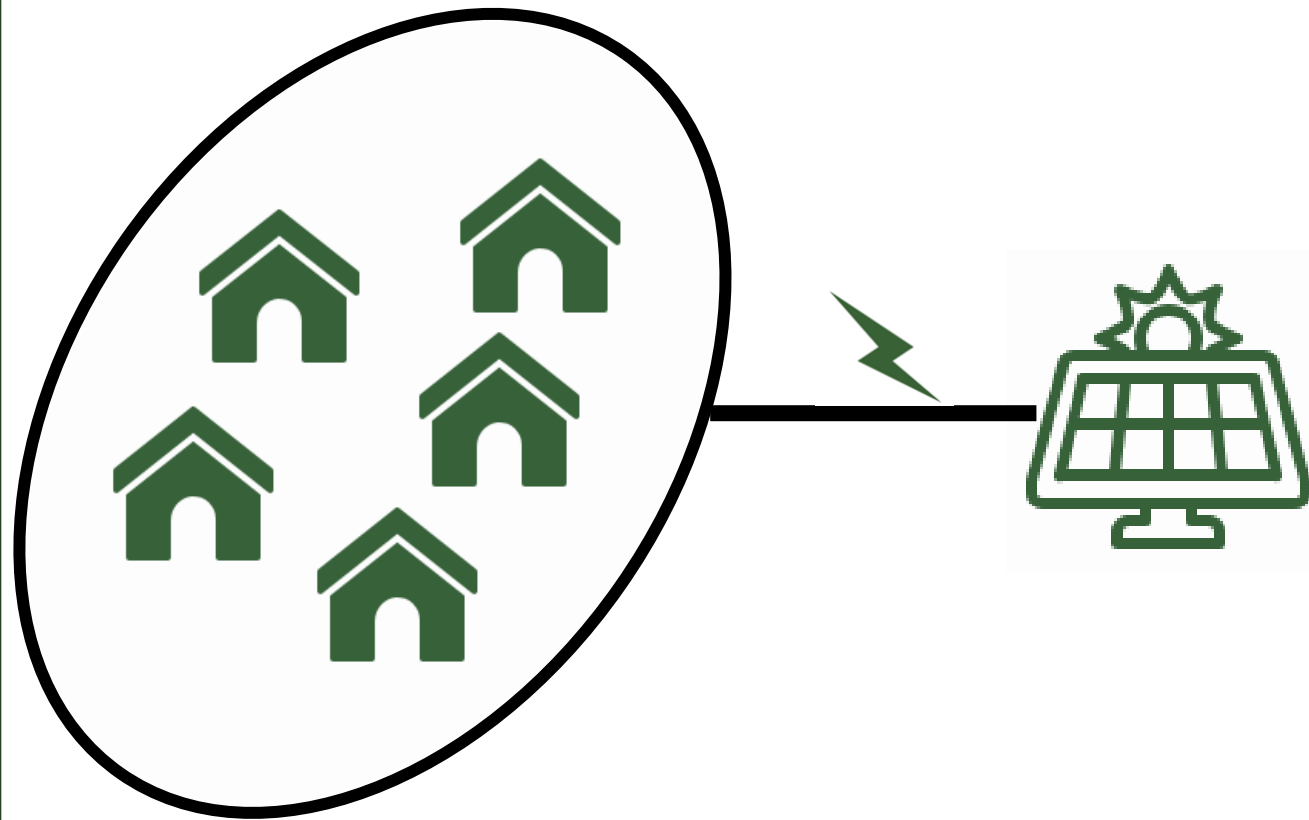
- ✓ Explain the significance of accurate load and energy resource estimation in designing off-grid systems
- ✓ Mathematically characterize off-grid system load by calculating the load profile, peak load, demand factor, and load factor
- ✓ Compare and contrast approaches to load estimation
- ✓ Assess and mathematically model solar energy resources

Introduction

- Appropriately designed off-grid systems balance the **cost** of the system with its ability to **reliably and safely meet the needs of the users**
- Off-grid system design requires knowledge of input energy characteristics (irradiance, wind speed, etc.) and energy output (load)
- Methods for characterizing and estimating load and energy resource covered in this module



Load Characteristics



What do we need to know about the load to design our system?

- ✓ How much load (average daily load and peak)
- ✓ When it is consumed (daily load profile)
- ✓ How load varies over time (day-to-day and year-to-year)

Average Daily Load

- Energy consumption (watthours/day)
- Depends on user type: household, commercial, industrial
- Distribution of average daily load has a “long tail”
 - most users use little energy, but a few use a lot
- Important for sizing energy production system and batteries

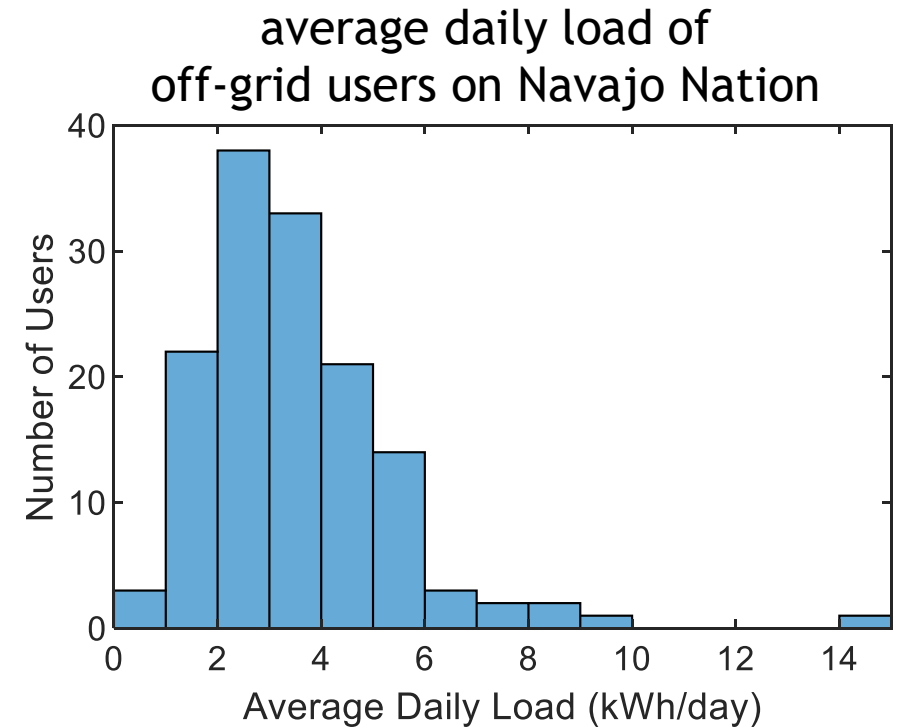
Representative Data

User Class	Avg. Daily Load (Wh)	Percent of Users (%)	Percent of Total Load (%)
Household (low)	35	75	15.5
Household (high)	250	20	29.6
Commercial (low)	1500	4.5	40.0
Commercial (high)	5000	0.5	14.8

Serving high-consumption users is critical to financial viability of off-grid systems

Average Daily Load

- Wide variation in average daily load, even among similar users
- Navajo Nation off-grid systems: some consumed <2 kWh/day others more than 8 kWh/day
- Consumption in SSA often less than 1 kWh/day (even less than 0.1 kWh/day)



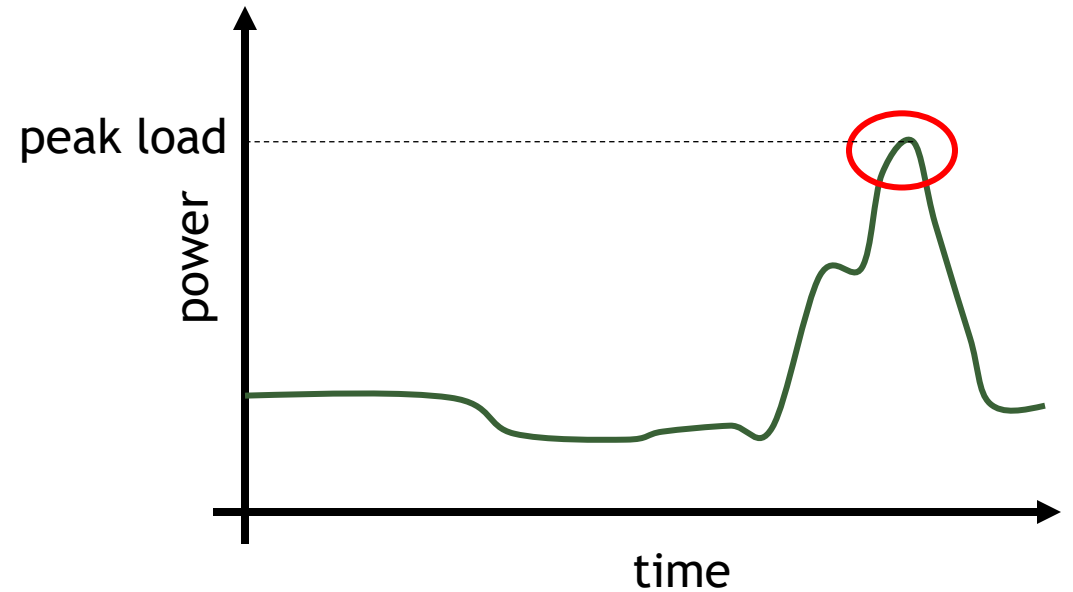
Average Daily Load

$$\bar{E} = \frac{\text{total energy consumed over } D \text{ days}}{D}$$

$\bar{E}$: Average daily load (kWh/day)
 D : number of days

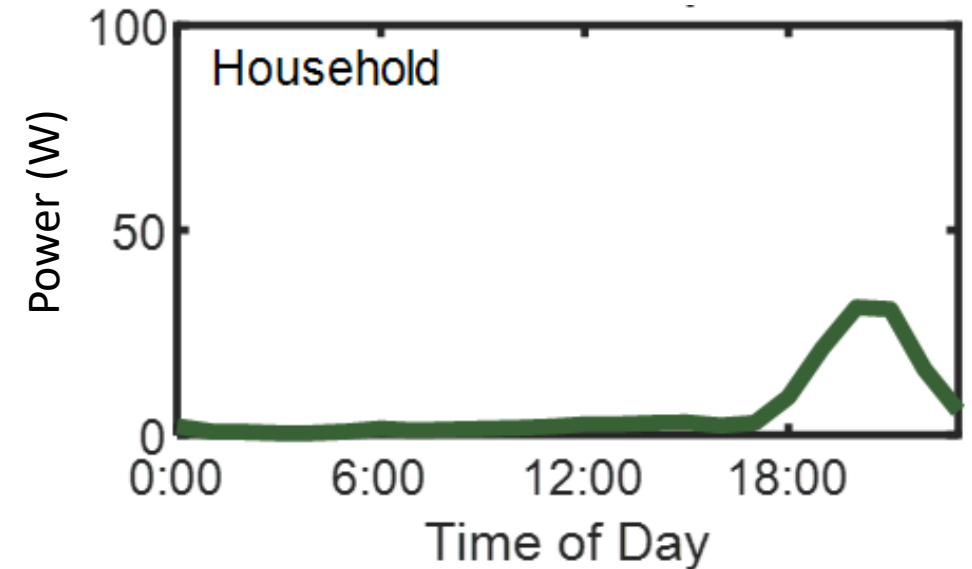
Peak Load

- Power consumption (watts)
- Maximum power consumed in a time period (e.g. year, lifetime)
- Inverters, generators, transformers, fuses, etc. should be rated above peak load

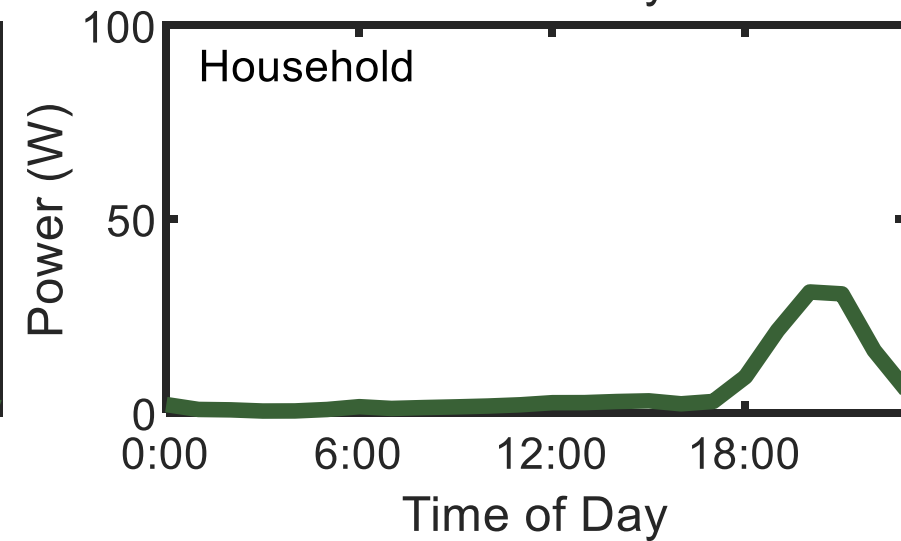
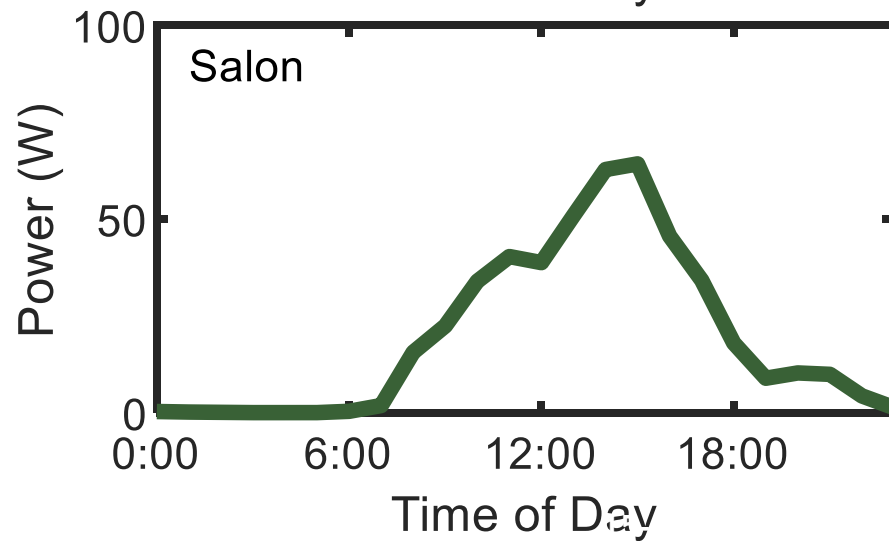
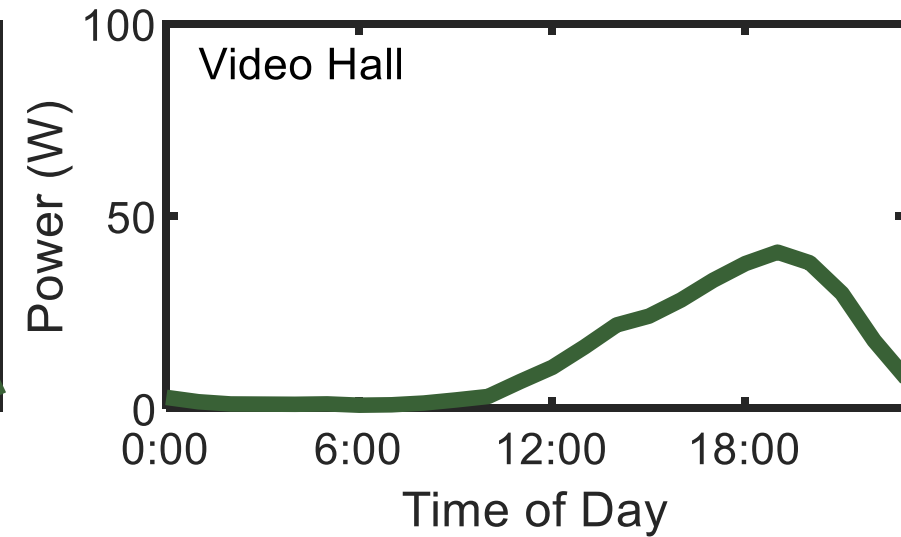
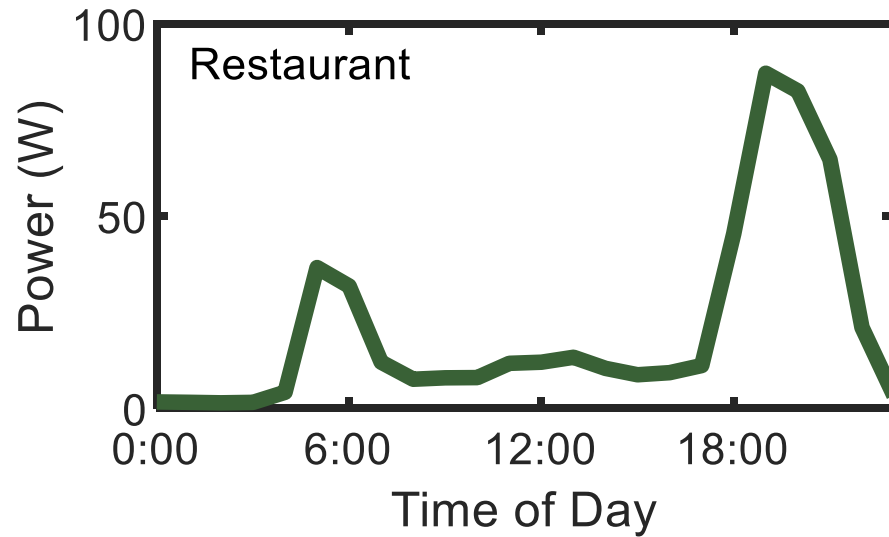


Load Profile

- Load Profile: *average load over the course of the day*
- Total area under the Load Profile equals average daily consumption
- Timing of consumption is important
 - Load co-incident with generation is desirable
 - Night-peaking load profiles are a poor fit for solar-powered systems



Load Profiles

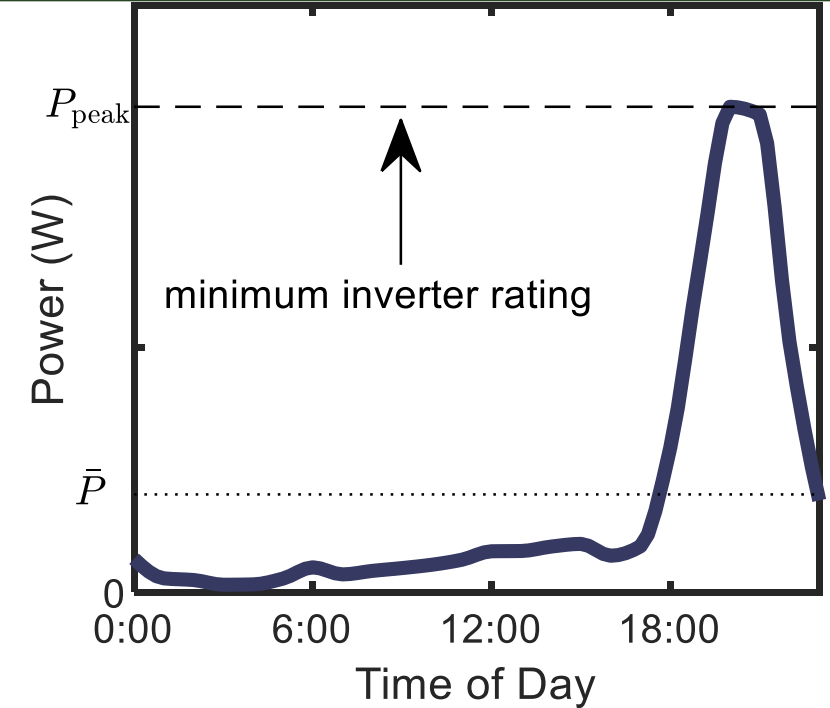


Load Factor (LF)

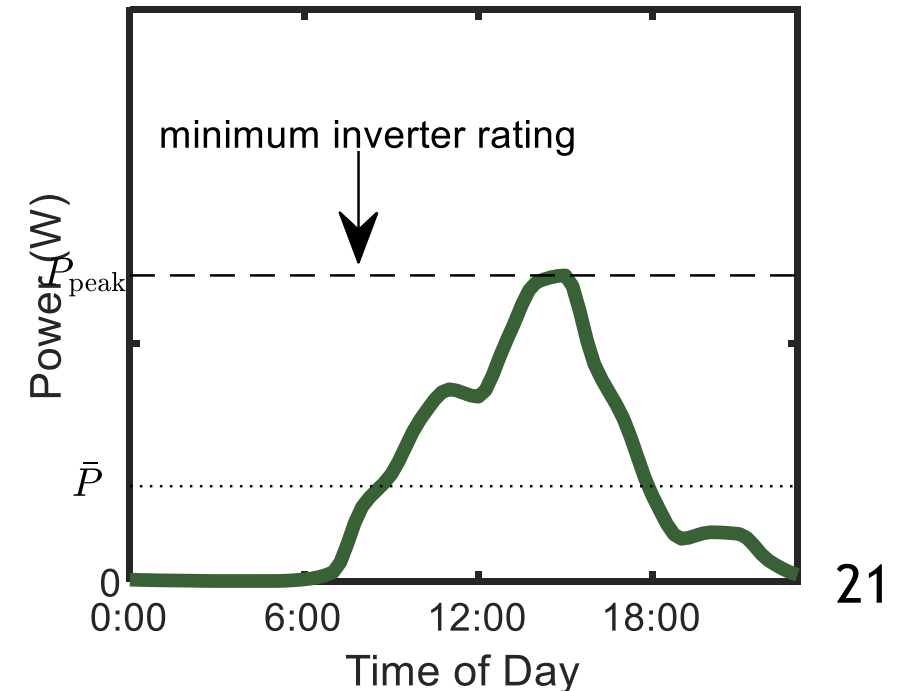
- Load Factor: *ratio of average power $\bar{P}$ and peak load P_{peak}*
- Higher load factors are desirable
 - lower equipment power ratings needed

$$LF = \frac{\bar{P}}{P_{peak}} = \frac{\bar{E}}{24 \times P_{peak}}$$

low load
factor (0.20)

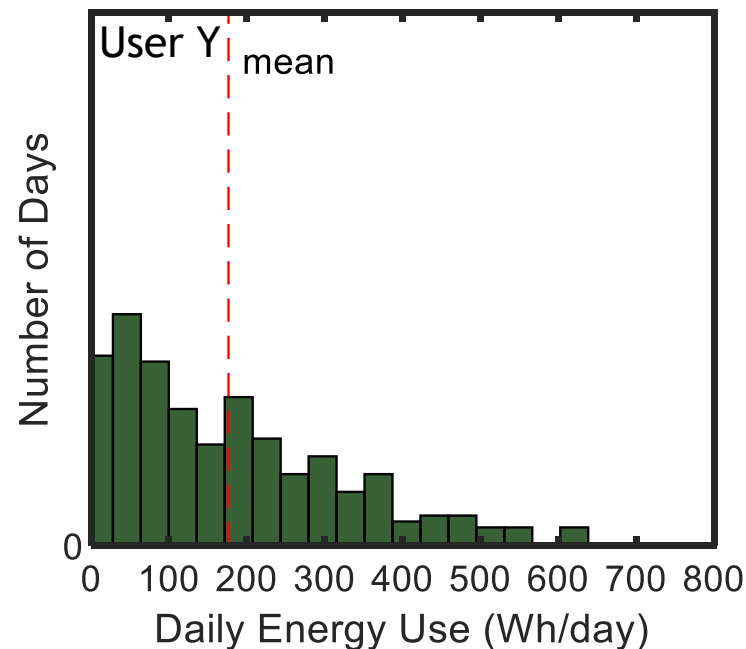
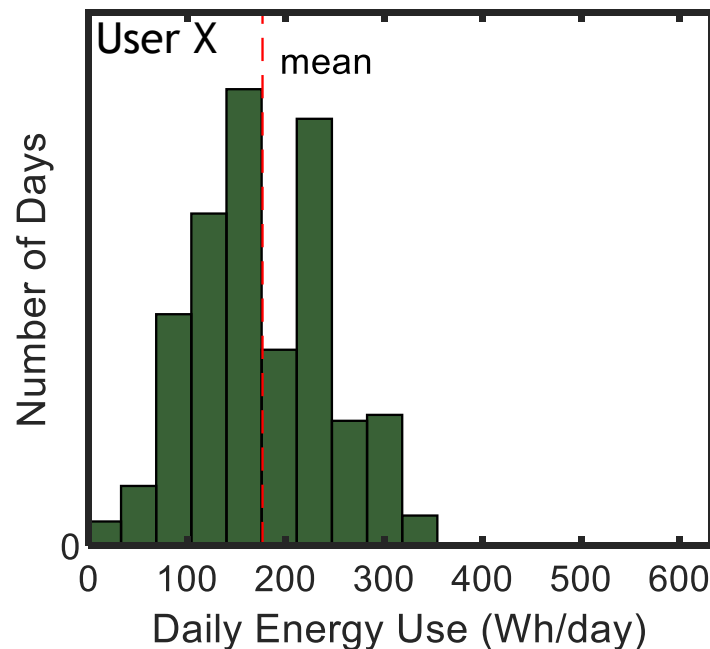


high load
factor (0.31)



Day-to-Day Variation

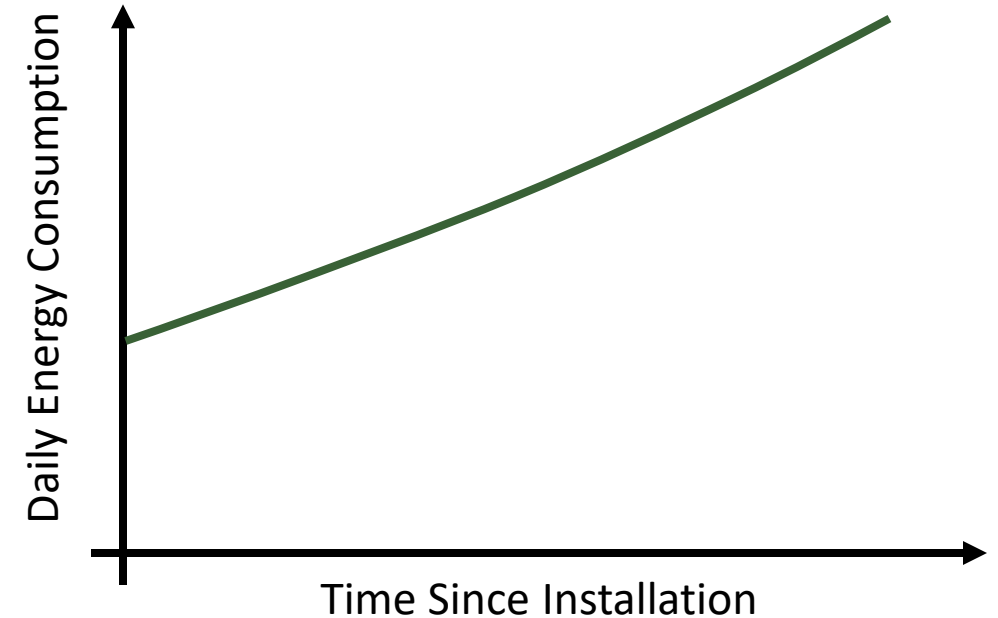
Reliability is dictated by extreme conditions, which is not captured by the average daily load



User X and Y have same average daily consumption, but User Y's consumption is more variable and requires a more expensive system to reliably serve

Year-to-Year Variation

- Consumption usually increases over time
 - 5-10% per year
- Load growth not consistent nor guaranteed
- Access to appliances a barrier
 - Appliance finance/leasing programs



Load Estimation Approaches

- Bottom-up
- Survey
- Regression (see book)
- Data-driven



Bottom-Up Estimation

- Requires knowledge of appliances and load profile
- Only realistic in certain scenarios (e.g. lighting only, or when usage is controllable)
- Energy estimation of user n

$$\hat{E}_{n,\text{load}} = \sum_{a=1}^A p_a \times \frac{K_a}{100} \times T_a$$

P_a : rated power of appliance a , (W)
 T : average hours of use per day of appliance a , (h)
 K_a : loading percentage appliance a , (%)
 A : total number of appliances

Bottom-Up Estimation

Quantity x Rating (W) x Duration of Use/Day x Loading Percentage = Energy Use/Day



$$5 \times 11\text{W} \times 4\text{hrs} \times 100/100 = 220 \text{ Wh}$$



$$1 \times 200\text{W} \times 24\text{hrs} \times 10/100 = 480 \text{ Wh}$$

700 Wh



Surveys

- Common method
- Estimate future energy use through surveys (door-to-door)
- Typical questions
 - What appliances do you expect to own?
 - What hours will you use them?
- Use bottom-up approach based on results
- Should be used with caution, as it is error-prone

Sources of Error

- ✓ Appliance ownership is mostly speculative
 - Appliance cost can delay ownership
 - Appliances can be acquired over time
- ✓ Appliance usage is also speculative
 - How much use can they afford?
 - Intermittent use is hard to estimate
- ✓ Inaccuracy of power ratings and load percentage
 - Many appliances do not consume constant power
 - How should stand-by power be accounted for?

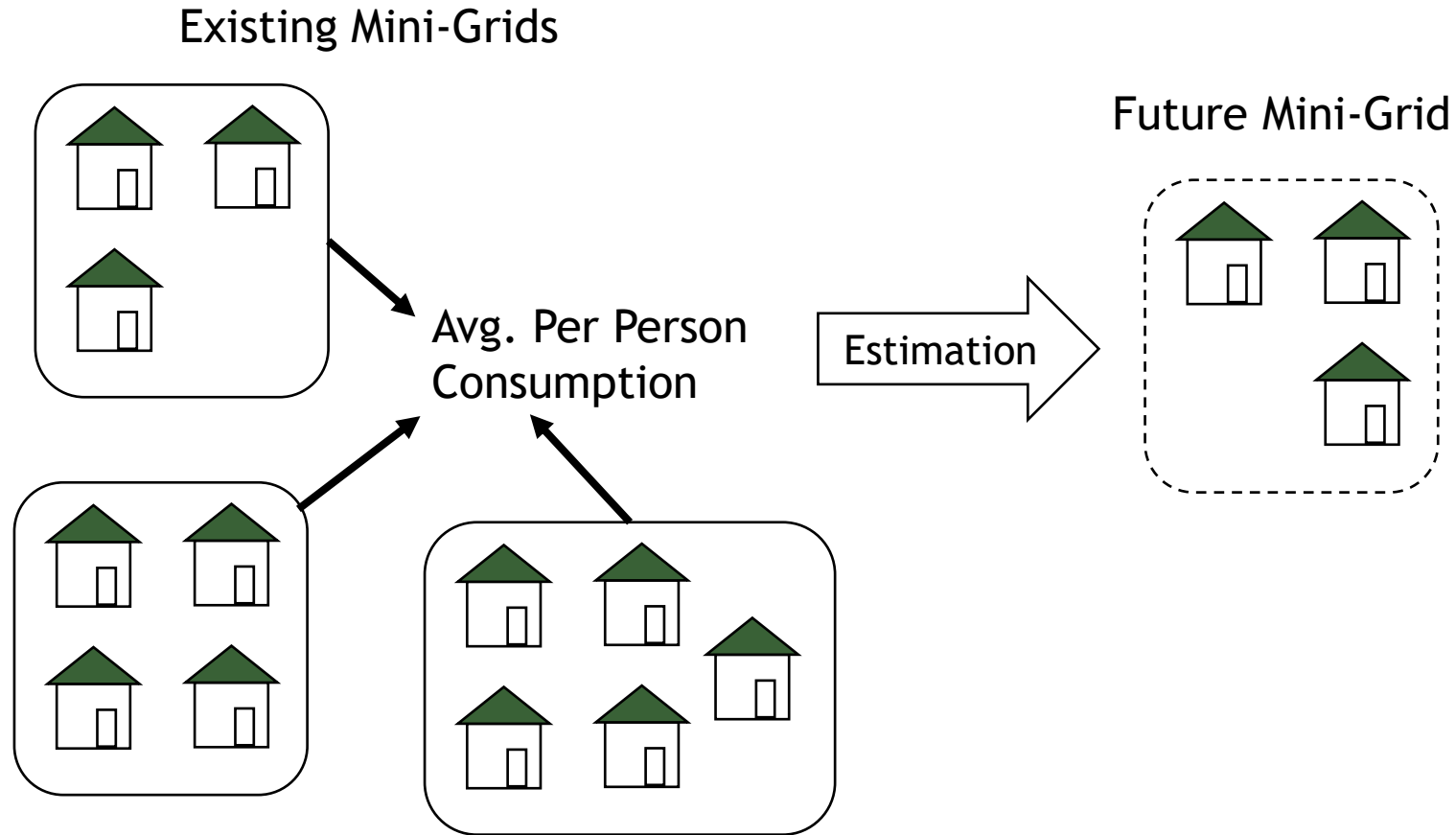
Surveyor bias!

Data-Driven

- Use historical consumption data from similar mini-grids to predict consumption of new mini-grids
- Requires access to historical data from many mini-grids
- Requires a framework for determining which mini-grid projects are similar



Data-Driven Prediction



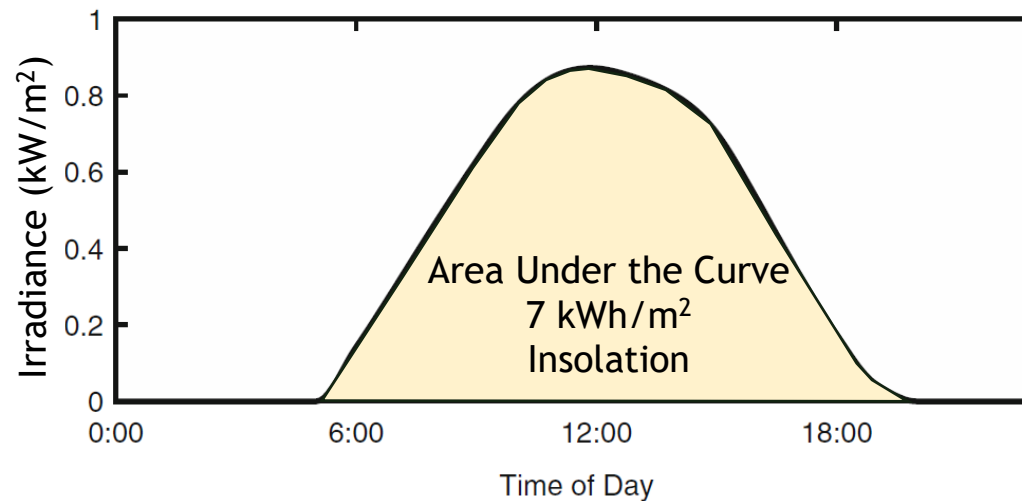
Energy Resource Characterization

- Load estimation considers the energy consumed, energy resource characterization considers the energy supplied
- Energy resource must be modeled before the system can be designed

Irradiance and Insolation

Irradiance: G , power density of sunlight (W/m^2)

Insolation: I , energy density of sunlight over a period of time ($\text{kWh}/\text{m}^2/\text{day}$)



Solar Resource

- Insolation over the course of a day d is:

$$I_d = \int_{t=0}^{24} G_d(t) dt$$

Units of I_d are kWh/m²/day if t is expressed in hours and G_d are in kW/m²

- The average insolation across D days in set $\mathcal{D}$ is simply:

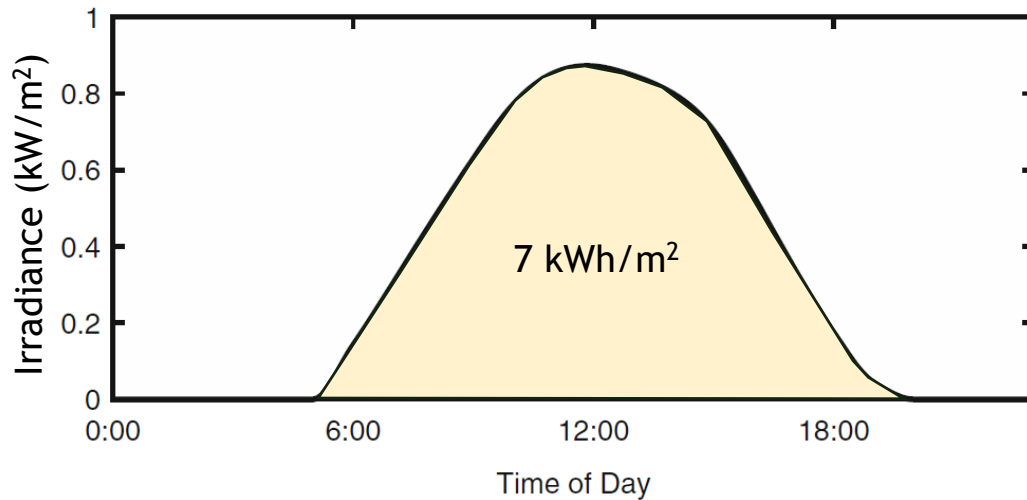
$$\bar{I}_D = \frac{\sum_{d \in \mathcal{D}} I_d}{D}$$

a month, year, 10 years, etc.

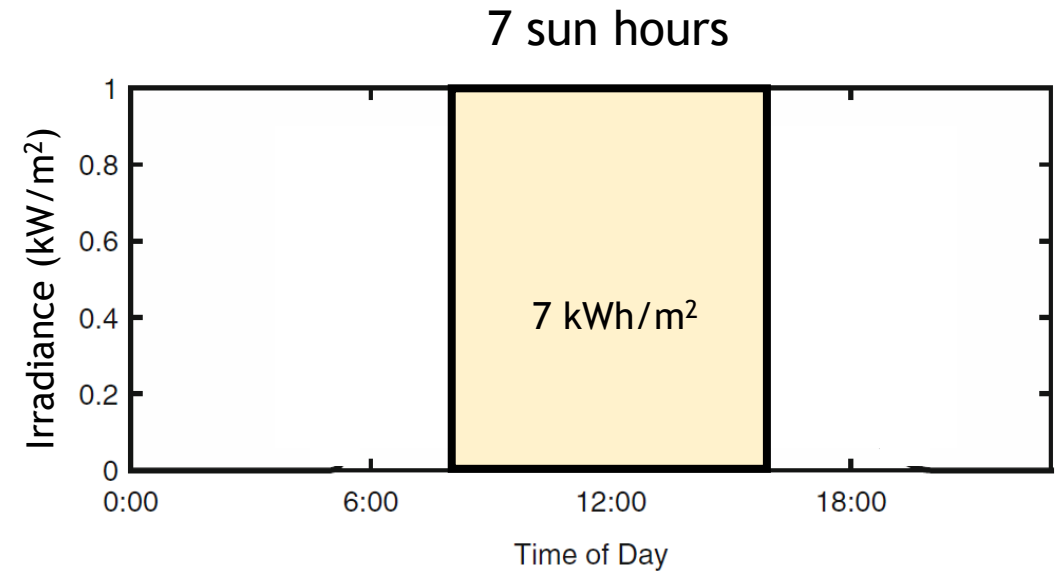
Sun-Hours (full sun hours)

- Average insolation is informally referred to as “sun hours” or “full sun hours”
- Assumes that under “full sun” conditions, the irradiance is 1000 W/m^2
 - one full sun hour therefore is 1.0 kWh/m^2
 - interpreted as the equivalent insolation of one hour of sun

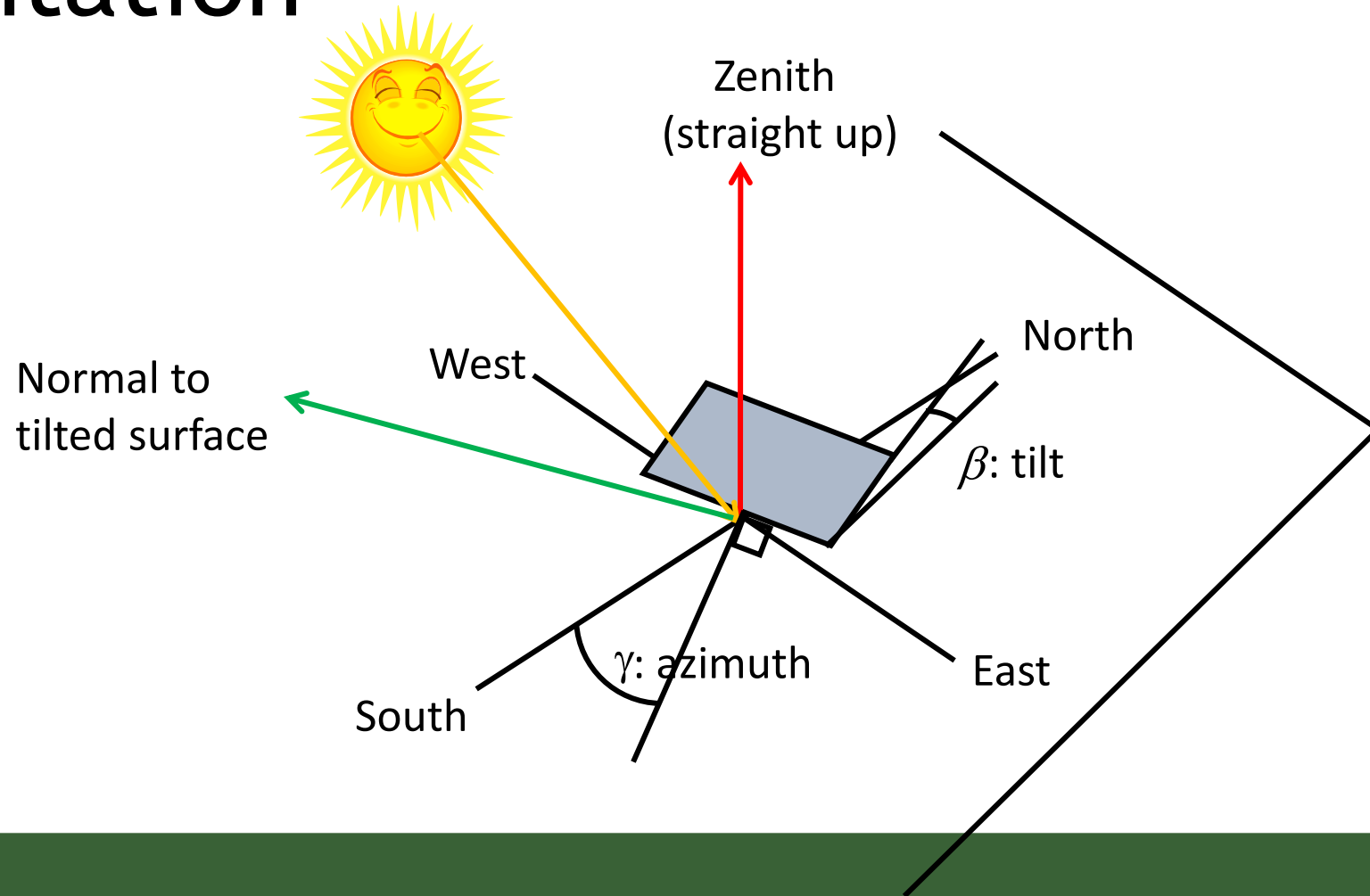
Sun-Hours (full sun hours)



=



Orientation



Plane-of-Array (POA) Irradiance

- Plane-of-array (POA) irradiance: irradiance that is incident to the surface of the PV array, accounting for its orientation (tilt, azimuth)
- Many databases report Global Horizontal Irradiance (GHI), which assumes PV array is horizontal (zero tilt)
- Be sure to use POA irradiance in calculations!
- Hereafter we assume irradiance and insolation values are POA

Capacity Factor

- Capacity factor is a metric to compare the utilization of a generation source
 - higher capacity factor indicates greater utilization
 - lower Capacity Factor may indicate that a generation source is oversized
- Unitless quantity, allowing large- and small-capacity projects to be compared

Capacity Factor

Capacity factor: ratio of actual (or estimated) energy production to the energy that could be produced if the generation source operated a full capacity continuously

$$\text{capacity factor} = \frac{\text{actual output}}{\text{theoretical maximum output}}$$

Capacity factor is often expressed as a percentage

$$\text{capacity factor} = \frac{\hat{E}}{T \times P_{\text{rated}}}$$

T : timeframe considered such as month, year, or life of system

Capacity Factor Example

A 1.5 kW PV array generates 8 kWh each day. The capacity factor is:

$$\text{capacity factor} = \frac{\hat{E}}{T \times P_{\text{rated}}} = \frac{8.0}{24 \times 1.5} = 0.22 \text{ (22\%)}$$

Capacity Factor of a PV Array

- If temperature effects are ignored, the power produced by a PV array is

$$P_{PV} = P_{STC}^* \times G$$

Note: we are assuming irradiance G is expressed in kW/m^2 , not W/m^2

- The estimated energy production for day d is therefore:

$$\hat{E}_{PV,d} = P_{STC}^* \int_{t=0}^{24} G_d(t) dt = P_{STC}^* I_d$$

Energy is equal PV rating x number of sun hours

Capacity Factor of a PV Array

- The estimated total production for a month is therefore:

$$\hat{E}_{PV,D} = \sum_{d \in \mathcal{D}} P_{STC}^* I_d = P_{STC}^* \sum_{d \in \mathcal{D}} I_d = P_{STC}^* \times \bar{I}_D \times D.$$

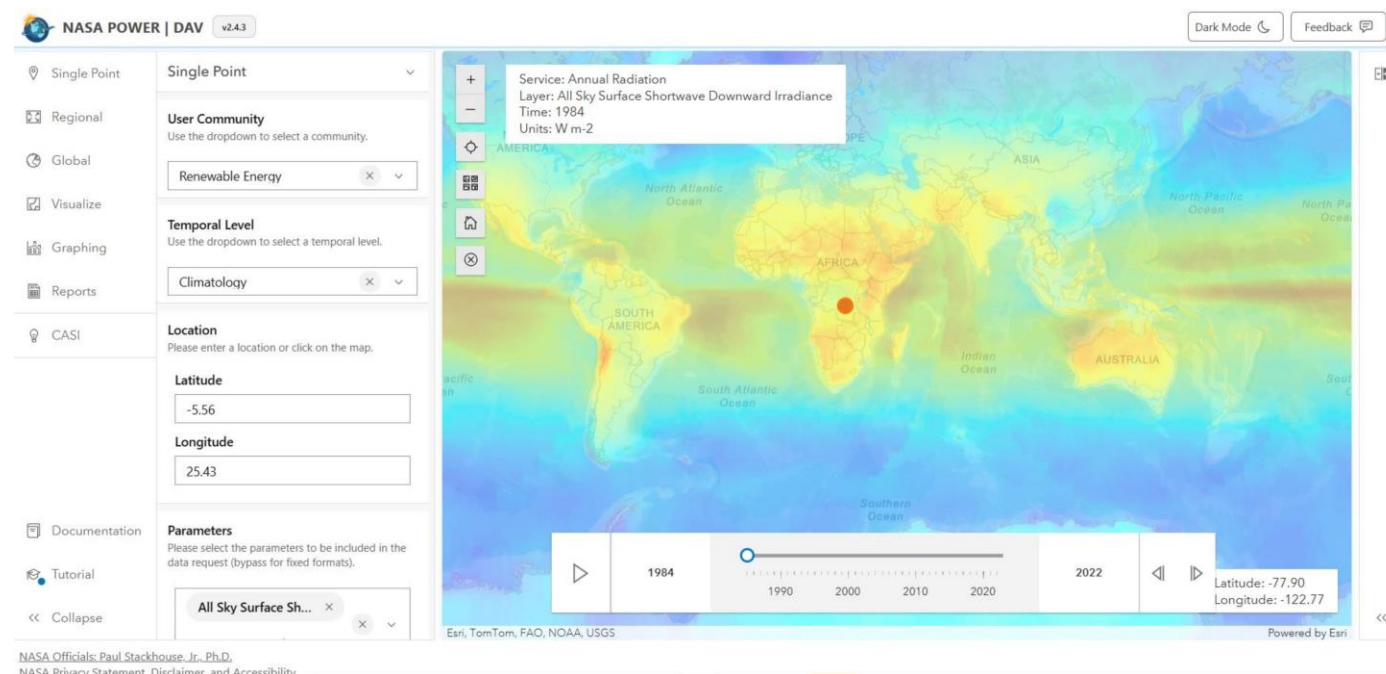
- And the Capacity Factor is:

$$capacity\ factor = \frac{\hat{E}_{PV,D}}{24 \times D \times P_{STC}^*} = \frac{P_{STC}^* \bar{I}_D D}{24 \times D \times P_{STC}^*} = \frac{\bar{I}_D}{24}$$

In other words, the Capacity Factor is independent of the PV array rating, and is simply the number of sun hours divided by 24

Solar Resource Databases

Insolation and other solar resource data for most locations can readily be found in online databases



NASA's Prediction of Worldwide Energy Resources (POWER) Data Access Viewer (DAV) interface. The data was obtained from the POWER Project's Climatology 2.4.3 version on 2024/12/22 (courtesy NASA)

15-Off-Grid System Load & Energy Resource Estimation © 2025 by Henry Louie is licensed under CC BY-NC-SA 4.0 www.drhenrylouie.com

POWER Single Point Data Access

1. Choose a User Community

SSE-Renewable Energy

2. Choose a Temporal Average

☐ Daily
☐ Interannual
☒ Climatology

3. Enter Lat/Lon or Add a Point to Map

9.0815

(-90 to +90 decimal degrees)

7.4806

(-180 to +180 decimal degrees)

Clear

4. Select Time Extent

Start Date

01/01/2015

(No date needed)

End Date

03/05/2015

(No date needed)

5. Select Output File Formats

☐ Select All
☒ ASCII
☐ CSV
☐ GeoJSON
☐ NetCDF

6. Select Parameters

(Limit 20 parameters)

The Climatology temporal period has the most parameters.

Parameter Charts

All Sky Insolation Incident on a Horizontal Surface ▾

Latitude: 9.0815 **Longitude:** 7.4806

Time Extent:

22 Year Solar Climatological Averages (Jul 1983 - Jun 2005)

30 Year Meteorology Climatological Averages (Jan 1984 - Dec 2013)

Elevation: 404.65 meters

Hover for charting tools ↓

Month	Insolation (kW-hr/m ² /day)
January	5.9
February	6.1
March	6.3
April	6.1
May	5.6
June	5.1
July	4.5
August	4.2
September	4.8
October	5.4
November	6.1
December	5.9

<https://power.larc.nasa.gov/data-access-viewer/>

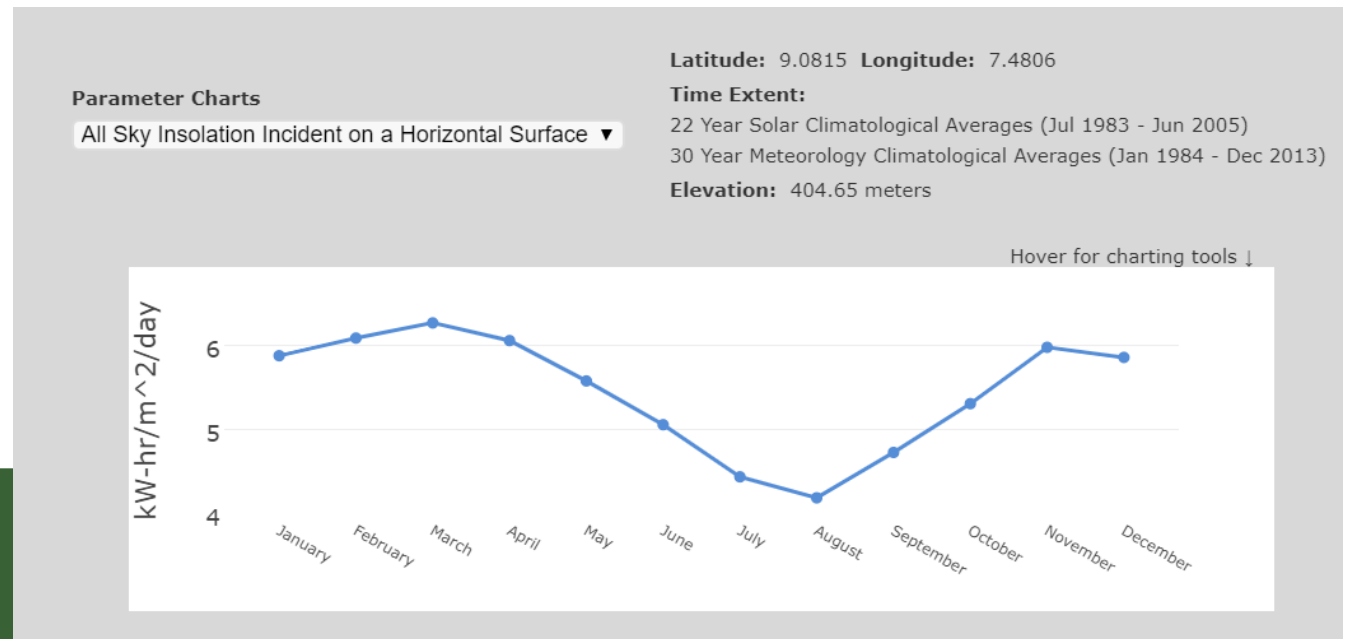
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44



Knowledge Check

The average insolation on a 350 W PV module for the month of September is $4.7 \text{ kWh/m}^2/\text{day}$. What is the average daily energy produced by the module? What is the capacity factor?





Knowledge Check

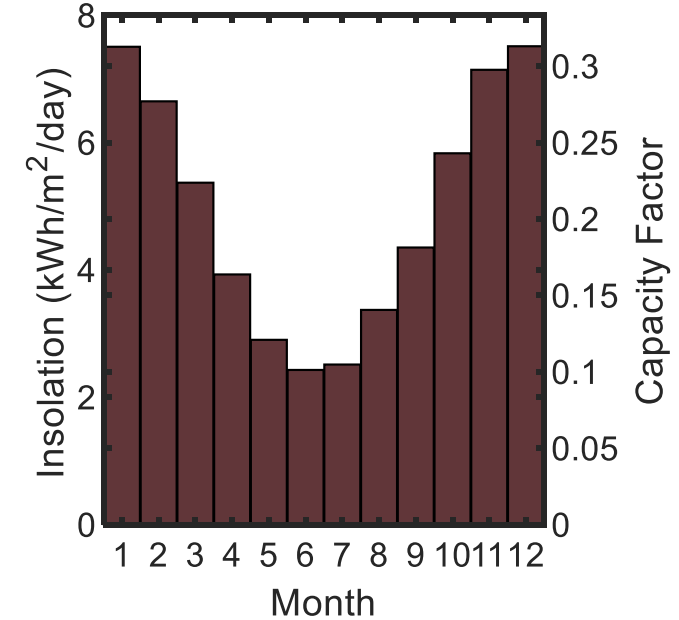
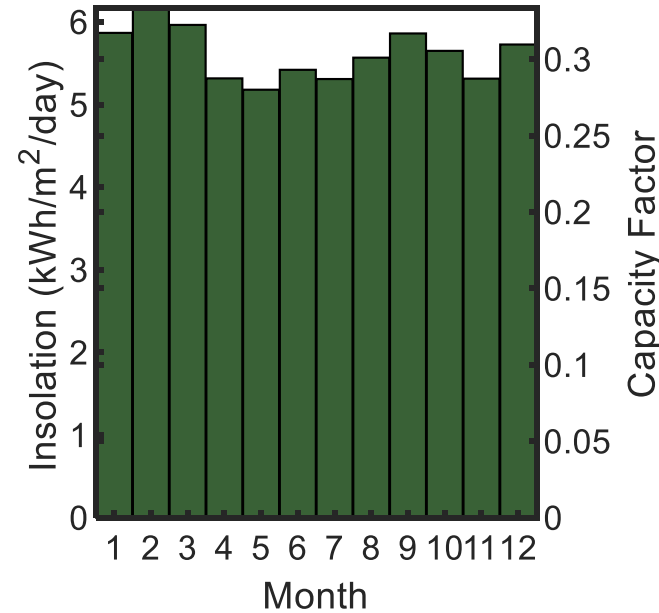
The average insolation on a 350 W PV module for the month of September is 4.7 kWh/m²/day. What is the average daily energy produced by the module? What is the capacity factor?

$$\bar{E}_{PV} = 350 \times 4.7 = 1645 \text{ Wh}$$

$$\text{capacity factor} = 100 \times \frac{1645}{350 \times 24} = 19.6\%$$

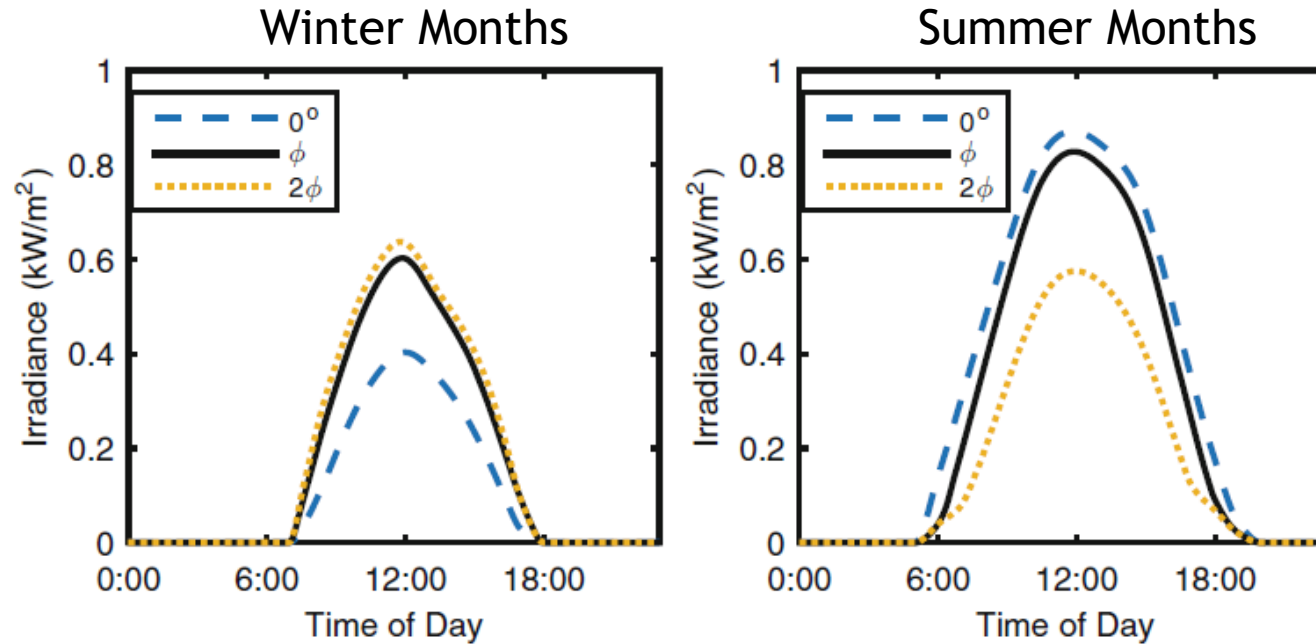
Capacity Factor is Influenced by

- Season (day of year)
- Location (lat. and long.)
- Weather conditions
- Orientation of array



Insolation and capacity factor for
a horizontal arrays near the equator and 34° S

Effects of Tilt



Optimal Tilt

Guideline: tilt the PV array at the latitude in which it is installed, and have it face the equator (i.e. face North in the southern hemisphere; face South in the northern hemisphere)

A minimum tilt of 5 to 10 degrees is advised to prevent collection of debris

Ellensburg, USA (47 °N)



(courtesy: H. Louie)

Singapore (1 °N)



(courtesy: H. Louie)

Module B: Off-Grid Energy Production System Design



ALSTOM FOUNDATION
FOR THE ENVIRONMENT



Community
Solutions
Initiative

SEATTLE UNIVERSITY



Learning Outcomes

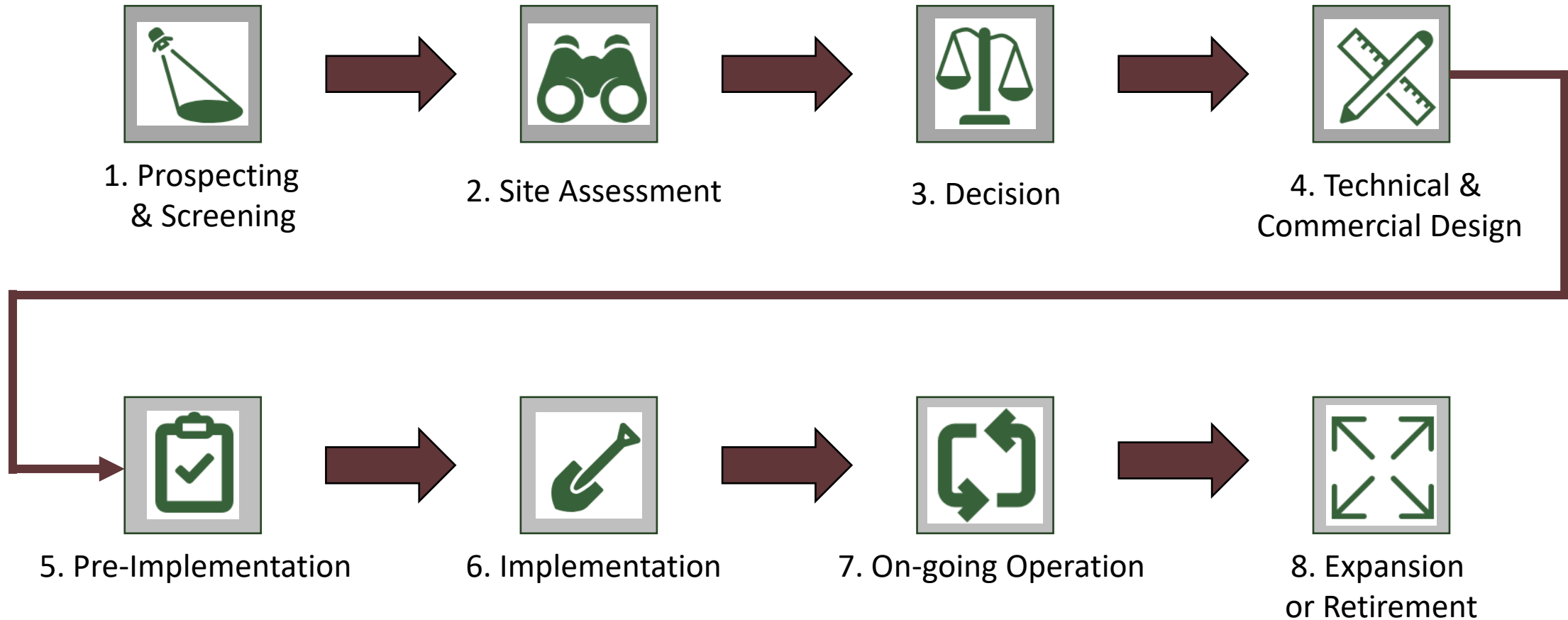
At the end of this lecture, you will be able to:

- ✓ Describe the phases of an off-grid system life cycle
- ✓ Design an off-grid system's energy production system based on estimates of the energy resource and load using an intuitive or numerical design approach
- ✓ Discuss the trade-off between cost and capability in off-grid system designs

Introduction

- Characteristics of estimated load and energy resource are used to design the energy production portion of an off-grid system
- Focus on mini-grid design, although many of the same concepts apply to standalone systems
- We will take the perspective of a mini-grid developer

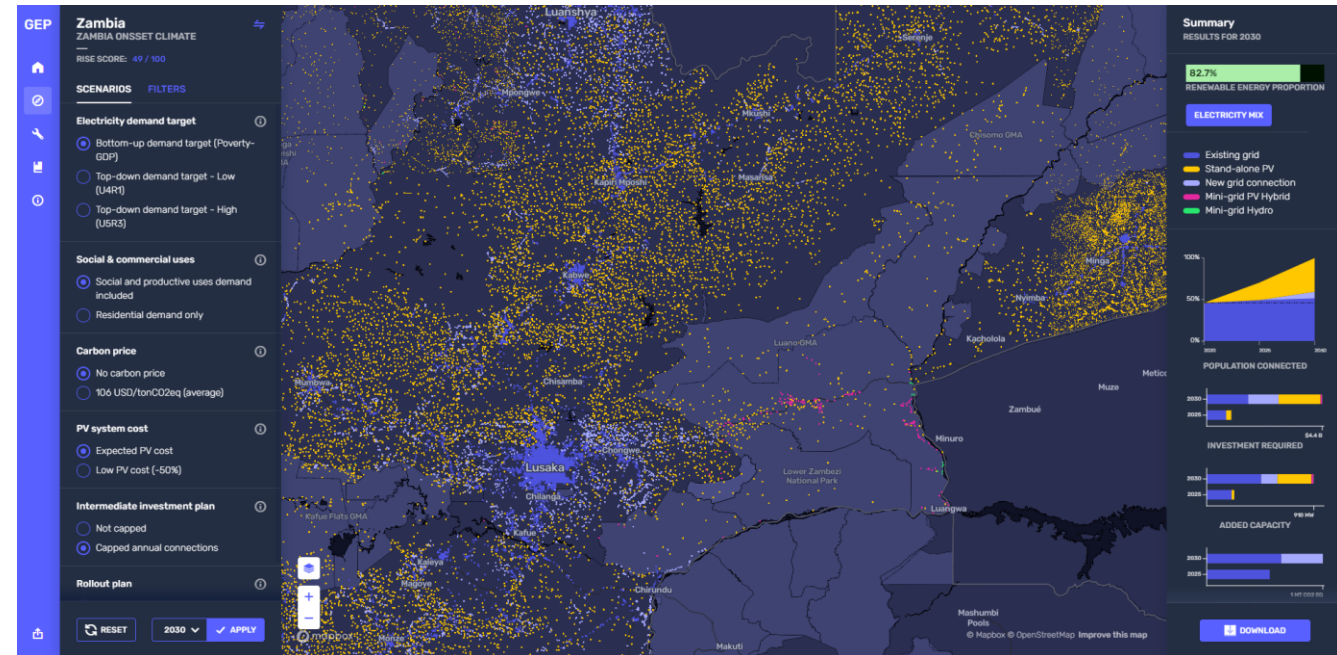
Off-Grid System Life Cycle





1. Prospecting & Screening

- Which community to choose?
- Success often depends on location
- Quickly and inexpensively screen potential communities
 - distance from existing grid
 - resource availability
 - other demographics
- Create short list of promising communities



Global Electrification Platform geospatial tool, which is part of the ENERGYDATA.INFO and World Bank Group Energy and Extractives Open Data and Analytics Initiative, and created by the KTH University (courtesy of World Bank Group, KTH University and the Energy Sector Management Assistance Program (ESMAP))



2. Site Assessment

On-site data collection

- observe community firsthand
- meet with local officials
- confirm secondary data are reasonable
- conduct surveys/focus groups
- collect preliminary energy resource data
- identify possible location for assets



(courtesy Kilowatts for Humanity)

2. Site Assessment

- Not all off-grid communities are suitable for mini-grids
- What characteristics make a community a good candidate?



Source: Google Earth

2. Site Assessment: Preferred Characteristics

- ✓ National grid is located far away (20 km or more) with no credible plans for it to be extended to the community
- ✓ No other off-grid systems installed or planned to be installed
- ✓ Estimated demand for electricity is high, and the planned uses are productive or improve the quality of life
- ✓ Sufficient ability and willingness to pay for electricity at a cost-reflective rate or a rate that aligns with the implementing organization's ability to operate the mini-grid

2. Site Assessment: Preferred Characteristics

- ✓ At least 50 structures (homes, businesses, etc.) within a 1 km radius (the area that can usually be served with low voltage distribution)
- ✓ Community is densely populated
- ✓ Basic infrastructure, including roads and cellular network coverage
- ✓ Politically stable
- ✓ Low risk of theft and vandalism

2. Site Assessment

Social/development preferred characteristics

- access to electricity is a high-priority developmental goal for the community
- access to electricity aligns with and supports other developmental goals, for example, healthcare and education
- community is able to organize itself to manage and operate the mini-grid (if applicable)



(courtesy Kilowatts for Humanity)



3. Decision

- Prioritize communities based on organizational objectives
 - profit
 - humanitarian impact
 - others
- Decision methods
 - PESTLE (political, environmental, social, technological, legal, economic) analysis
 - risk matrices
 - Theory of Change
 - others



4. Technical & Commercial Design

- Detailed technical and commercial plan design and development
- Iterative and inter-related process
- If design is not projected to meet certain technical or business targets, consider next community on list
 - capital expense
 - operating expense
 - access tier
 - Average Revenue Per User (ARPU)



5. Pre-Implementation

- Permitting (if applicable)
- Vendor identification and contracting
- Procurement
 - importing equipment (may take many months)
- Community/customer identification and orientation
- Base line monitoring & evaluation to determine impact (see Chap. 19)



(Courtesy A. Stewart)



6. Implementation

- Construction of energy production, distribution and end-user system
- Implementation can be quick---as few as several days
- Commissioning and verification



(Courtesy P. Dauenhauer)



7. On-Going Operation

- Serving users
- Maintenance and repair
- Technical data collection
- Commercial data collection
- Social data collection



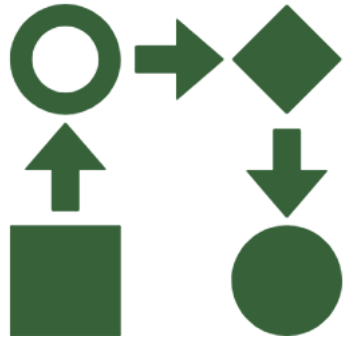
(Courtesy PowerGen Renewable Energy)



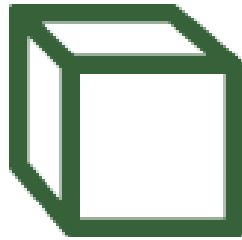
8. Expansion or Retirement

- Expansion
 - serve additional users
 - improve access tier
- Retirement
 - restore land and environment to original condition
 - dispose, re-use or re-cycle equipment in a responsible way
 - community relations

Design Steps



1. Architecture
Selection



2. Component
Sizing



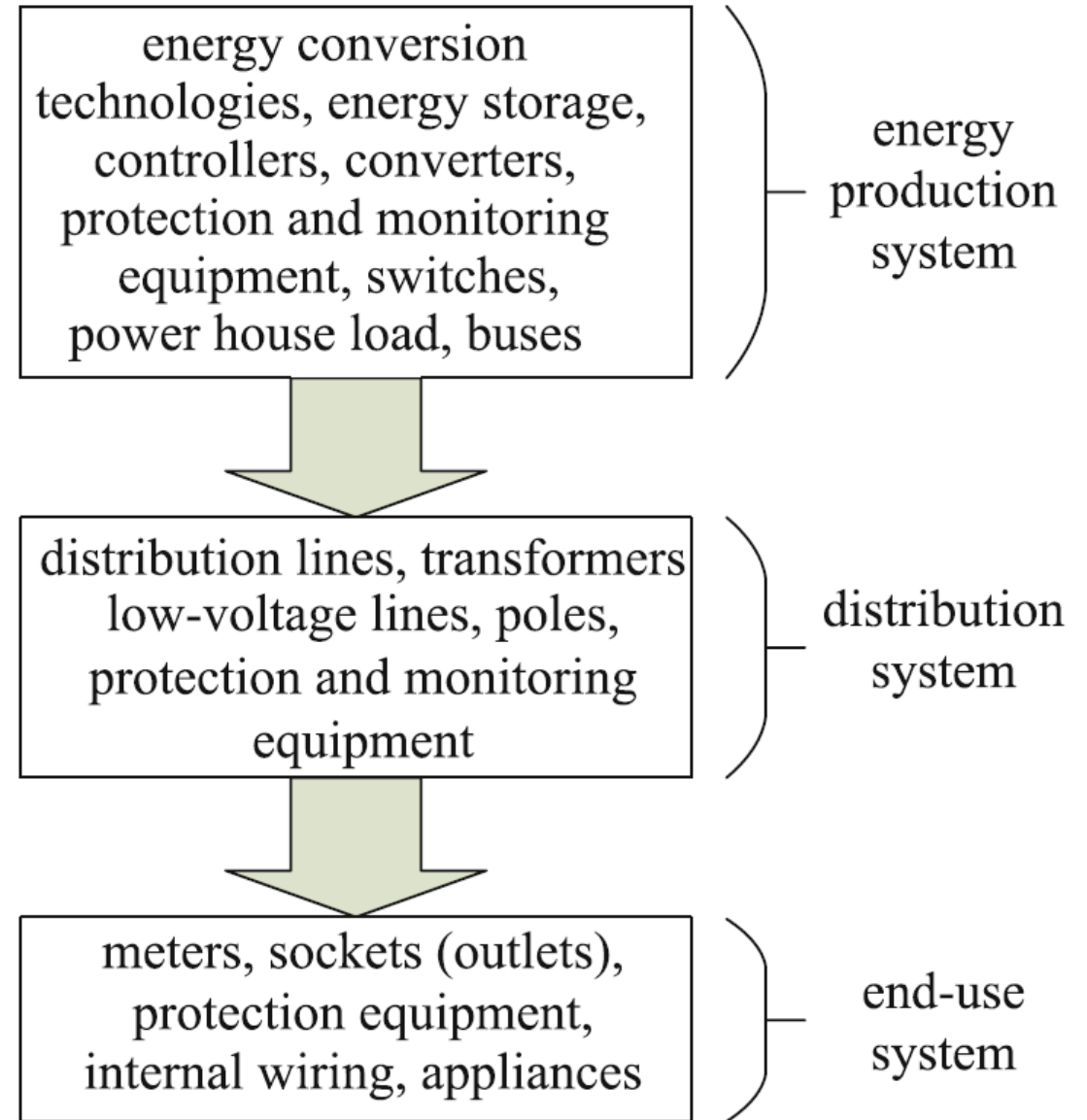
3. Component
Selection & Layout



4. Final
Electrical Design

See text for examples
of electrical design drawings

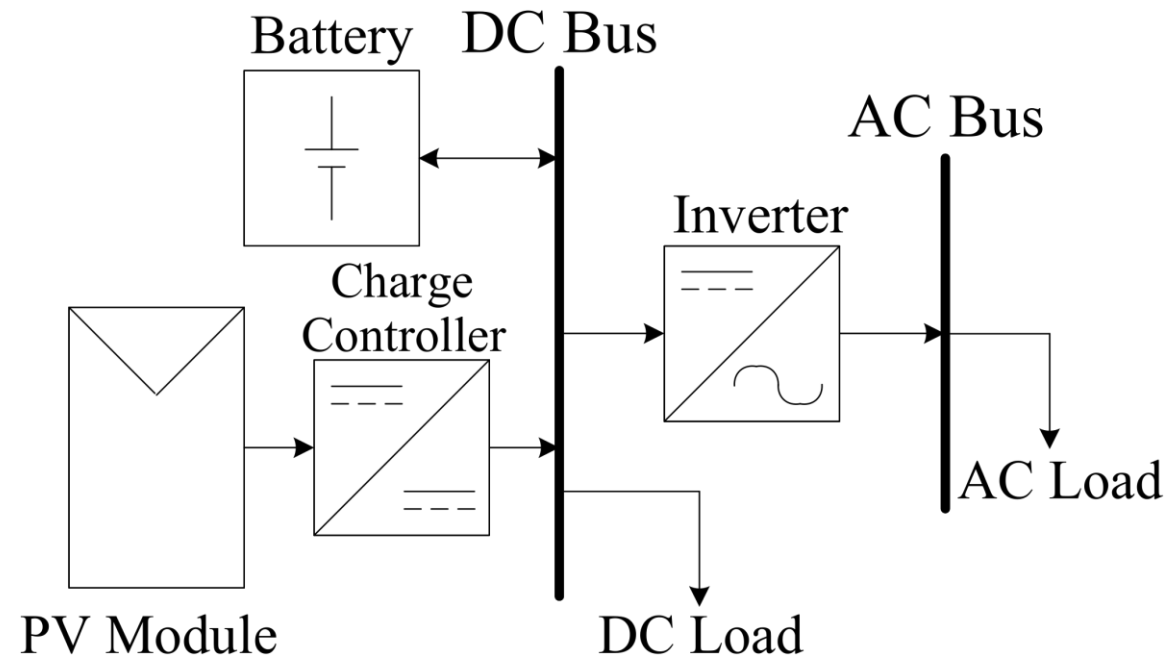
Mini-Grid Sub-Systems



Architecture Selection

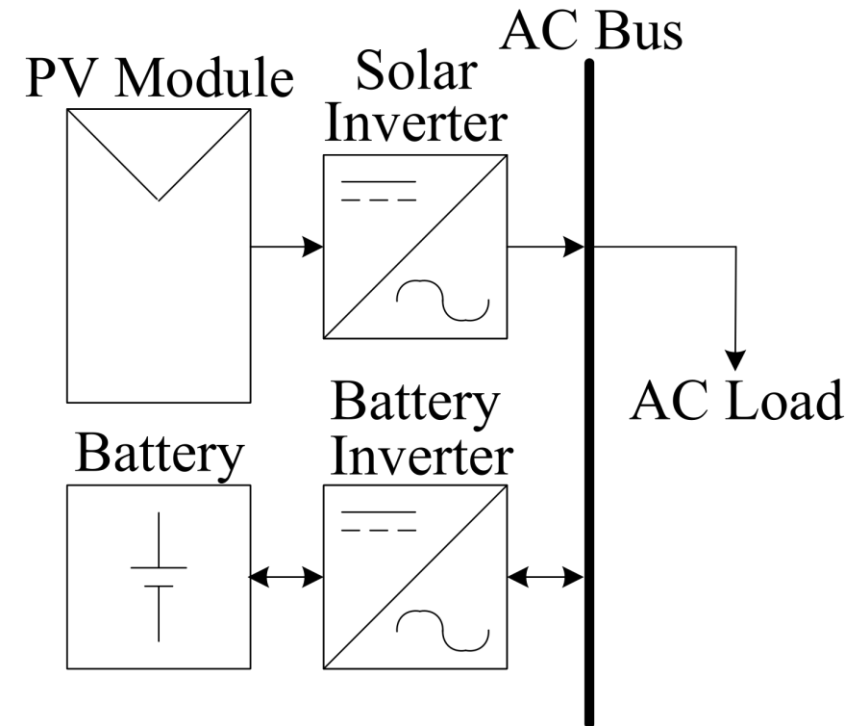
- Define which energy conversion technologies, energy storage, converters, and controllers will be used, as well as the coupling type (AC, DC, AC-DC)
- Architecture largely depends on energy resource characteristics and load requirements
- See Chap. 4 for designing a valid architecture

DC-Coupled PV Systems



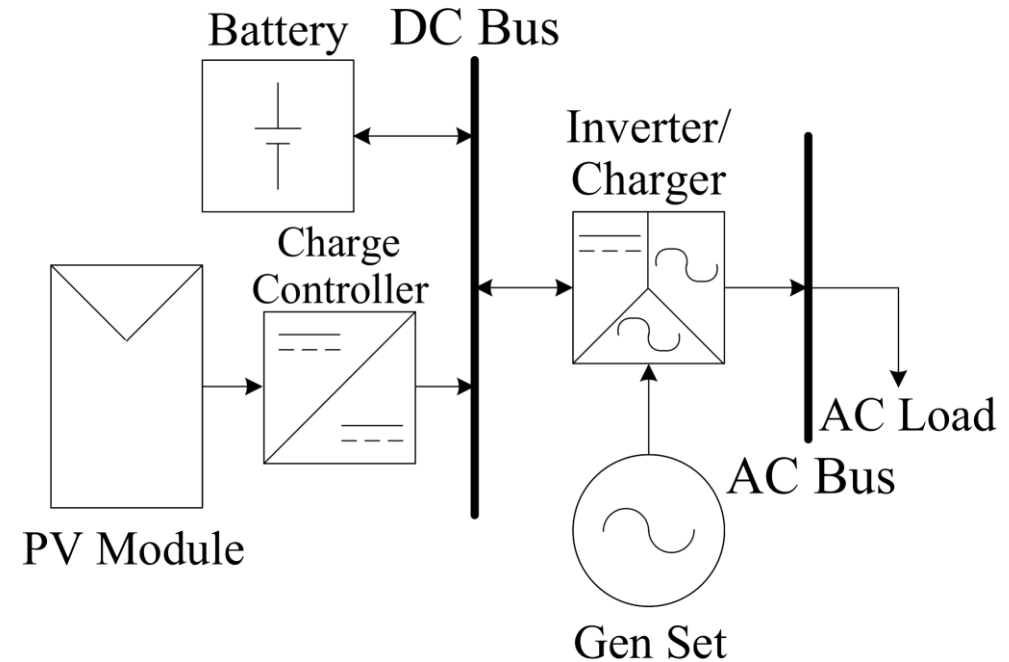
AC-Coupled PV Systems

- Solar inverters can be used to couple PV modules to the AC bus
- Battery inverter “forms” the AC bus and the solar inverters synchronize to it



Hybrid Systems: Switched Architecture with Battery Charging

- Inverter is bi-directional and can synchronize with gen set
- Gen set power to recharge battery and/or supply load
- Gen set and inverter can simultaneously supply load



Component Sizing

Use an intuitive or numerical design approach to determine the required ratings of the components to achieve the desired reliability or tier of service



Intuitive

Design by standards or guidelines to size system components



Numerical

Design/analysis through computer-aided simulation

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
- IEEE 2030.10: Standard for dc microgrids for rural and remote electricity access applications
- IEC TS 62257: Recommendations for renewable energy and hybrid systems for rural electrification
- Others



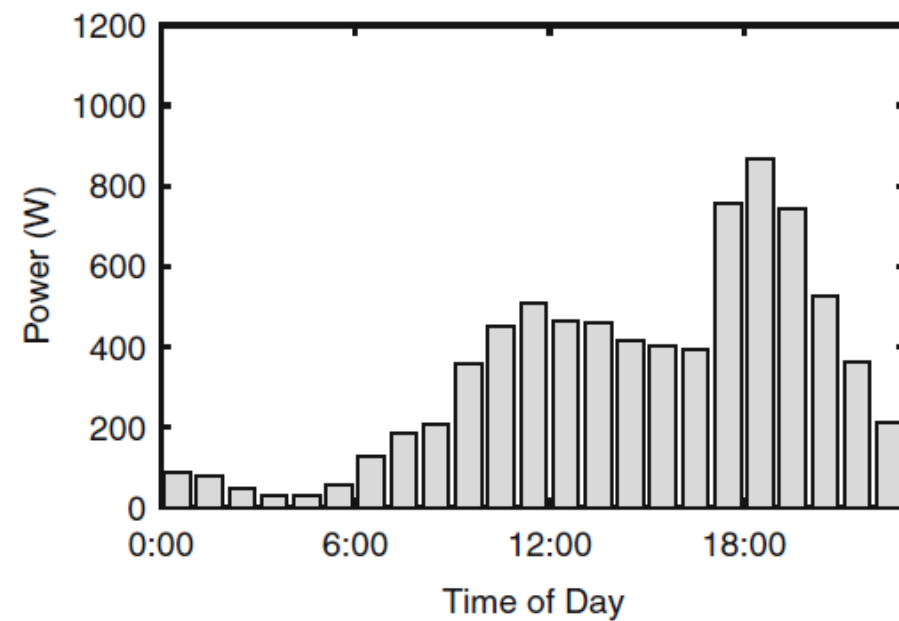
Intuitive Design Example: Mwase

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 230 VAC at 50 Hz
- No acceptable WECS, MHP or biomass resources
- Design to accommodate 5 years of growth

Load Estimation & Characterization

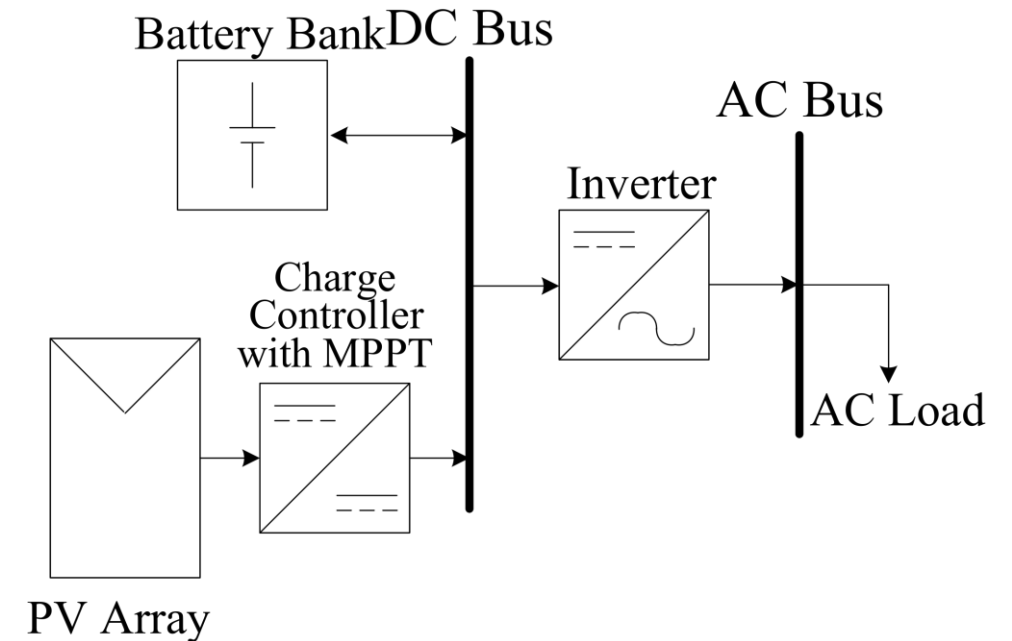
- Survey method used to produce load profile
 - individual loads are aggregated into single load profile
 - assumed weekday is the same as weekend
- Load growth estimate: 5% per year



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

Architecture Selection

- Battery for overnight load
- Inverter to supply AC load
- Charge controller to properly charge battery
- MPPT to maximize power from the PV array



Voltage Level Selection

- AC bus voltage: 230 V, 50 Hz to be compatible with available appliances
- DC bus voltage depends on:
 - average daily load
 - nominal voltage of battery cell
 - electrical distance between DC bus components (to minimize loss)
 - power capacity of the system
 - safety
 - availability of compatible components

Voltage Level Selection

Guidelines based on average daily load

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

Inverter Design

- 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)

Inverter Design

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

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

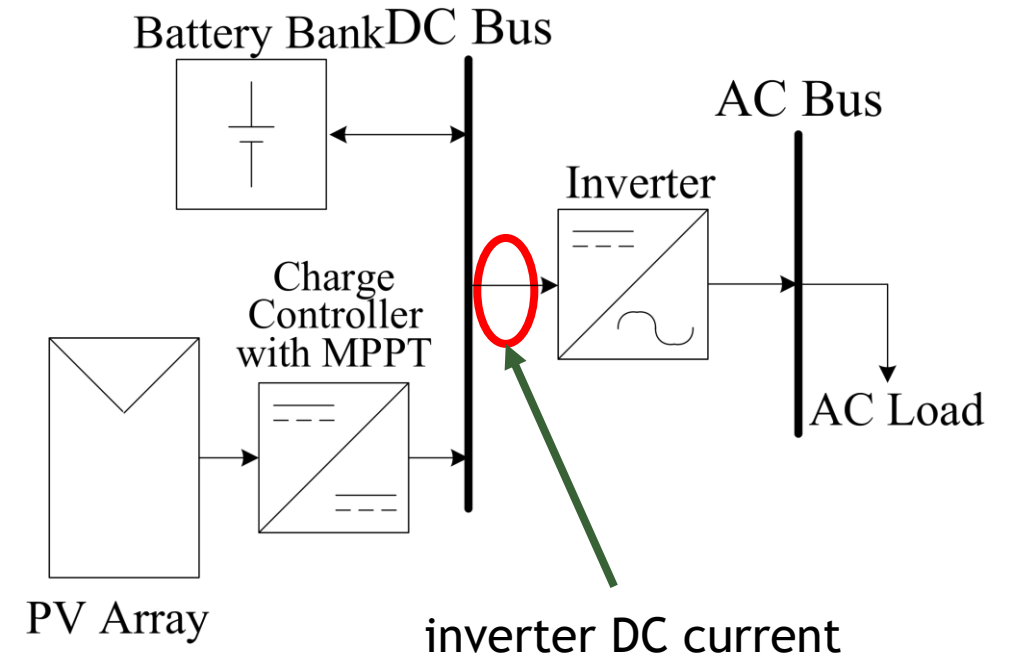
Inverter Power Requirement = 1.94 x (1 + 0.20) = 2.33 kW

Maximum Inverter DC Current

Needed as input to battery design

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

estimate from inverter efficiency curve and load profile



Maximum Inverter DC Current

Maximum inverter DC current

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

Assume efficiency is 85%

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

round up to 58 A

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 (THD, see Chap. 14)
 - Low Voltage Disconnect functionality
 - ability to operate in parallel with other inverters or AC sources

Battery Bank Design

- Energy storage designed independently from the energy source (PV array)
- Factors affecting size
 - DC bus voltage
 - required discharge current
 - desired reliability (days of autonomy)

Average Battery Load

Express average daily load in amphours

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

Mwase system:

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

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: <1 to +3 days
 - doubling days of autonomy does not double reliability

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

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%

Discharge Current for Battery Bank Capacity

- 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)

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 58 A (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

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

$$C'_x = C_x \times \frac{1}{\text{DoD}_{\text{max}}}$$


Maximum depth-of-discharge

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

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, then increase battery capacity

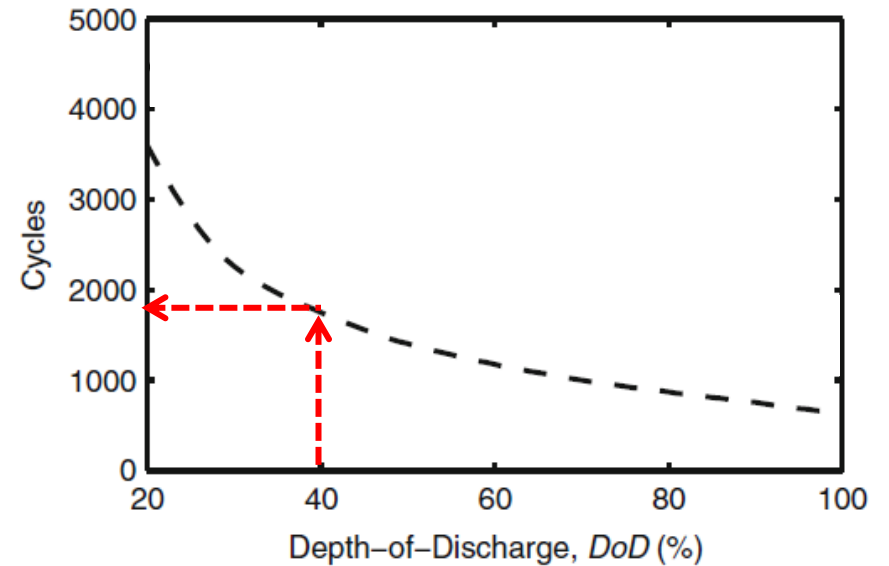
$$\text{Daily depth-of-discharge} = 100 \times \frac{\text{Avg. Daily Load}}{\text{Battery Bank Capacity}}$$

Daily Depth-of-Discharge

Mwase system (AGM batteries)

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

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



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

Battery Bank Design Margin

Apply a design margin to account for

- load estimation error
- variability of daily load
- effects of temperature
- other losses

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

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 58 A (C-rate of 0.07C, hour rate of 14.25 h)

Battery Choice

Assume selected battery has parameters

- Chemistry: lead-acid (gel)
- Nominal voltage: 2 V
- Cycle life: 1825 @50% DoD

	10 hr (42 A, 0.1C)	20 hr (22.5 A, 0.05C)	100 hr (5.4 A, 0.01C)
Capacity	420 Ah	450 Ah	540 Ah

Battery Bank Configuration

Design the configuration of the battery bank

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

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

Battery Bank Configuration

Battery considered is lead acid (2 V nominal voltage)

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

$$\text{Number of Series Batteries} = \frac{48}{2} = 24 \text{ batteries}$$

Battery Bank Configuration

Use capacity based on $827.21 \text{ Ah} / 58 \text{ A} = 14.25 \text{ hour rate}$
(0.07C)

	10 hr (42 A, 0.1C)	20 hr (22.5 A, 0.05C)	100 hr (5.4 A, 0.01C)
Capacity	420 Ah	450 Ah	540 Ah

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 430 Ah (or estimate using Peukert's Equation)

Battery Bank Configuration

	10 hr (42 A, 0.1C)	20 hr (22.5 A, 0.05C)	100 hr (5.4 A, 0.01C)
Capacity	420 Ah	450 Ah	540 Ah

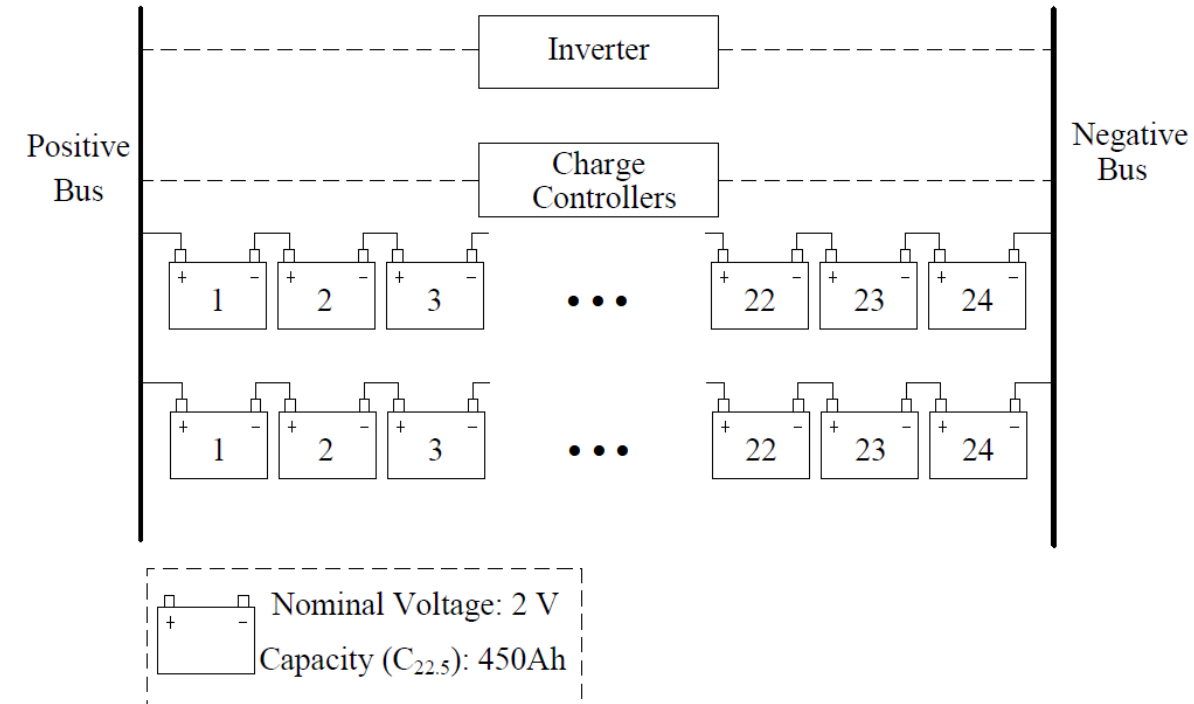
$$\text{Number of Battery Bank Strings} = \frac{\text{Required Battery Bank Capacity}}{\text{Individual Battery Capacity}}$$

$$\text{Number of Battery Bank Strings} = \frac{827.21 \text{ Ah}}{430 \text{ Ah}} = 1.92 \text{ strings}$$

Round up to 2 strings

Battery Bank Design

- Two strings of 24 batteries
- Each string supplies $58/2 = 29$ A during peak load



Average daily load of 246.25 Ah resulted in a battery bank with capacity of 900 Ah (450 x 2)

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

PV Array Tilt

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

Solar Resource & Tilt Selection

Average Daily Insolation (kWh/m²/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)

Energy Source Design

- Average energy produced

$$\text{capacity factor} = \frac{\bar{I}}{24}$$

$$E_{\text{PV}} = 24 \times \text{capacity factor} \times P_{\text{PV, rated}} = \bar{I} \times P_{\text{PV, rated}}$$

- Ignoring losses, energy from PV array (E_{PV}) must equal the average daily load with January's average daily insolation

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

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)

Accounting for Losses

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

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

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

Temperature Effects

- PV production is decreased when cell temperature surpasses STC temperature (25 °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%

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

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)

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

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
- PV array layout must be compatible with charge controller

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

Rounded up to 14

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, two-stage for lithium ion)

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

PV Module

Parameters of PV module under consideration:

Parameter	Module Actual
Maximum Power	0.350 kW
Optimum Operating Voltage (V^*)	38.54 V
Optimum Operating Current (I^*)	9.08 A
Open Circuit Voltage (V_{OC}), STC	47.43 V
Short Circuit Current (I_{SC}), STC	9.49 A
Short Circuit Current Temp. Coeff. (α_i)	0.04 %/K
Open Circuit Temp. Coeff. (α_v)	-0.29 %/K
Max. Power Temp. Coeff. (α_p)	-0.38 %/K
NOCT	45 °C

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

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

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

Round down to 3

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

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

Represents the case of irradiance at 1250 W/m²

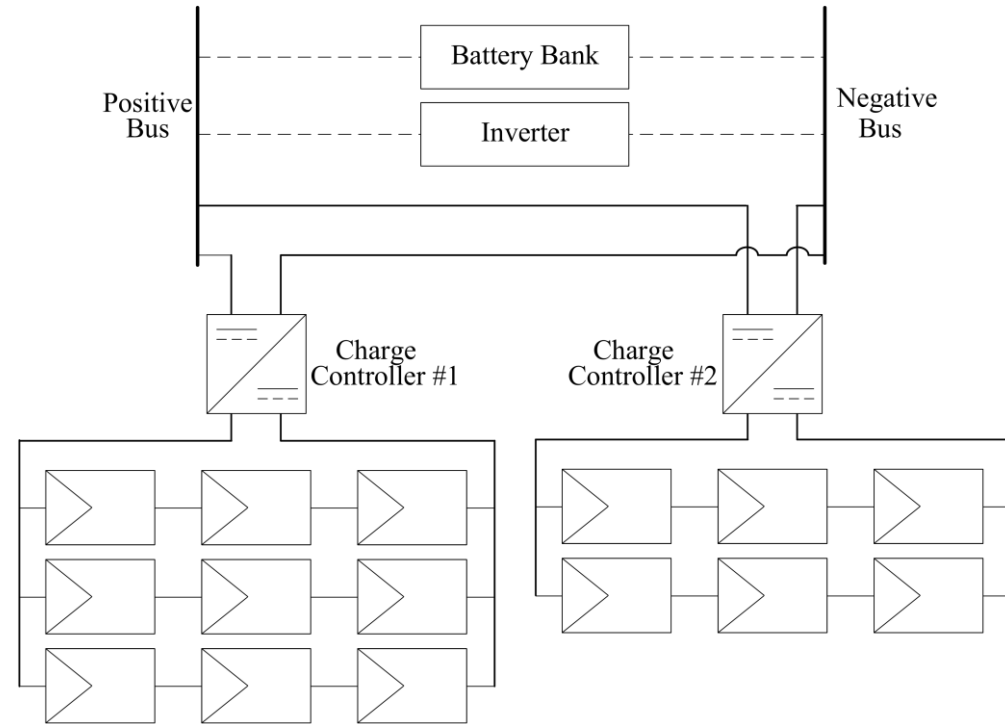
Round down to 5

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 greater than 14

PV Array Layout

Several other layouts possible



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)

Numerical Design

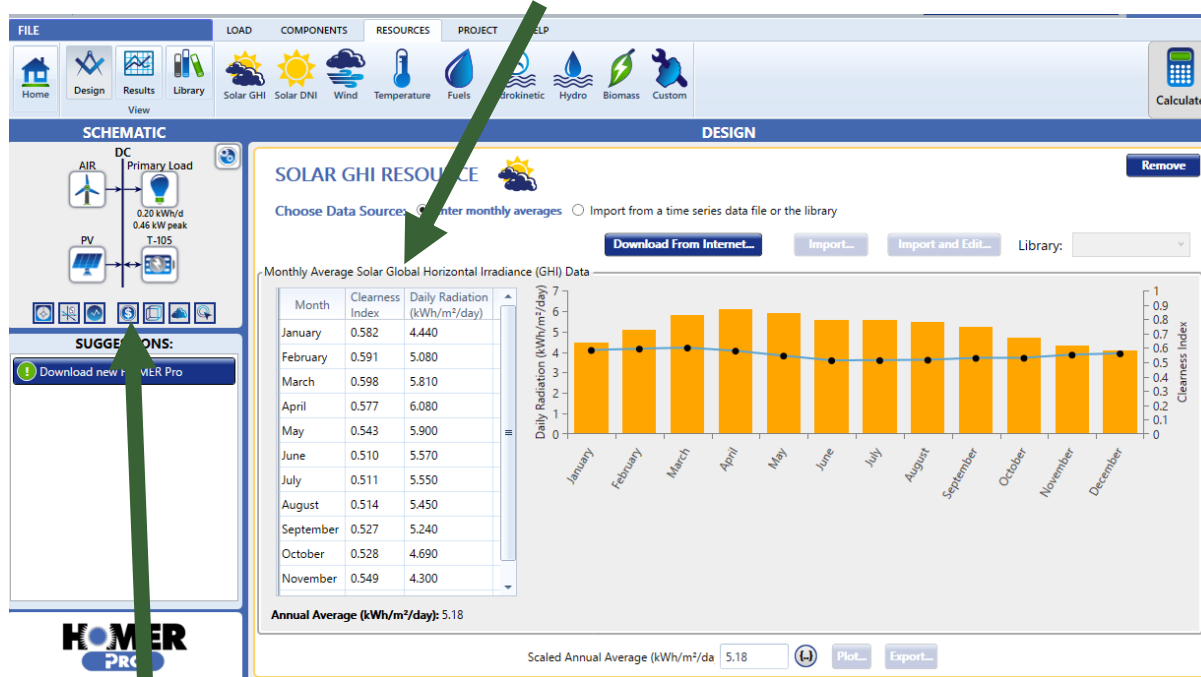
- Particularly useful for hybrid systems and those with complex control
- Allows for cost/reliability trade-offs of different designs to be recognized
- Input data requirements are high
- Results are only as good as the input information



“garbage in, garbage out”

Example: HOMER

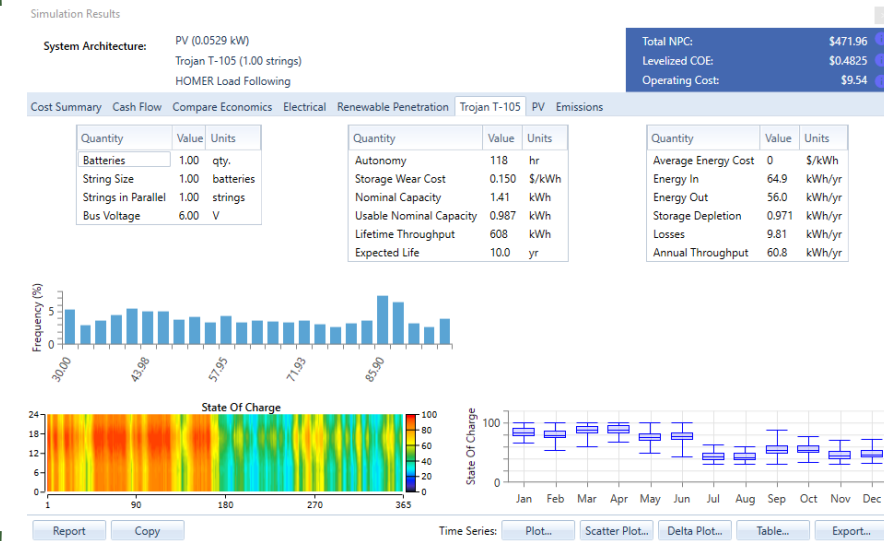
Resource Input



(courtesy of HOMER Pro from UL Solutions)

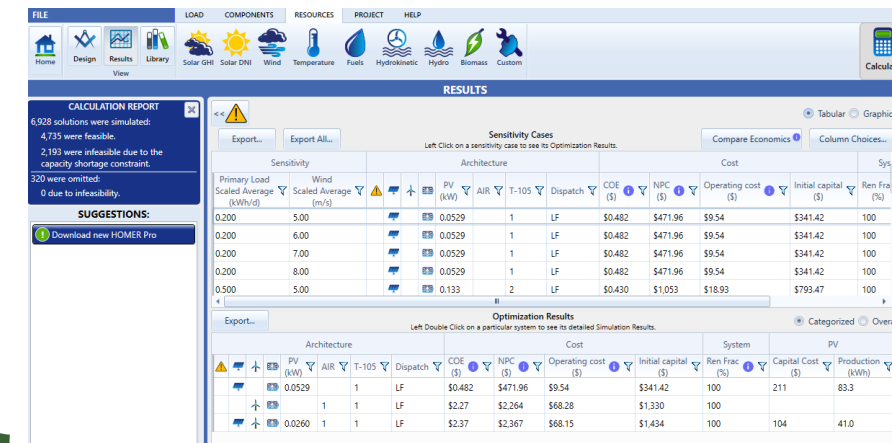
System Architecture

Simulation Results



(courtesy of HOMER Pro from UL Solutions)

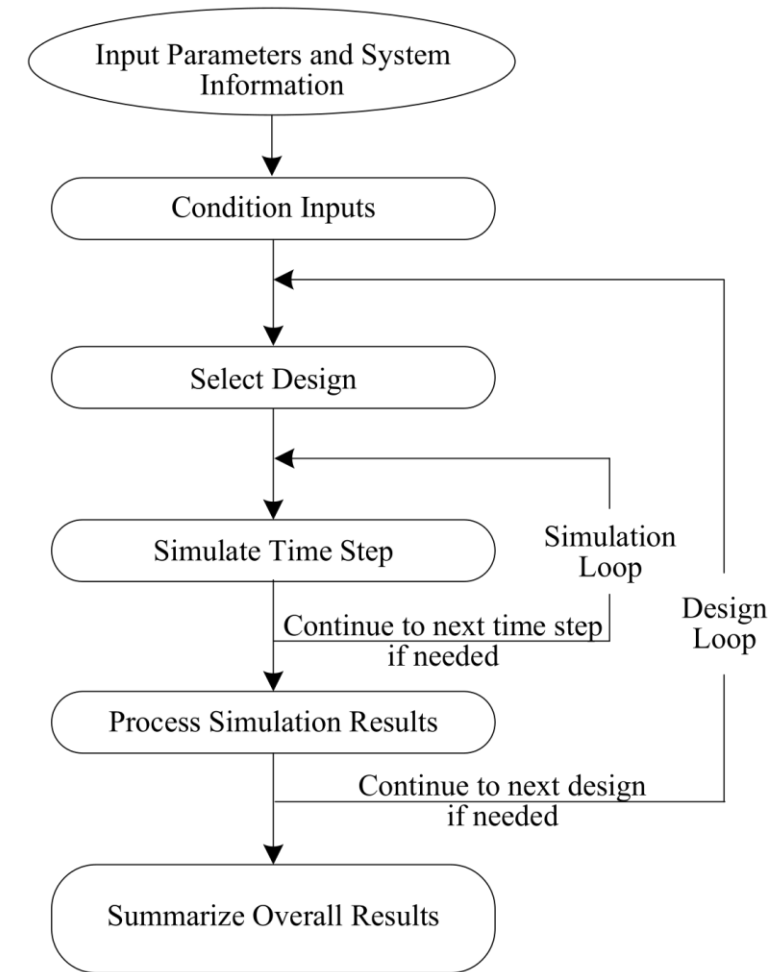
Optimization Results



(courtesy of HOMER Pro from UL Solutions)

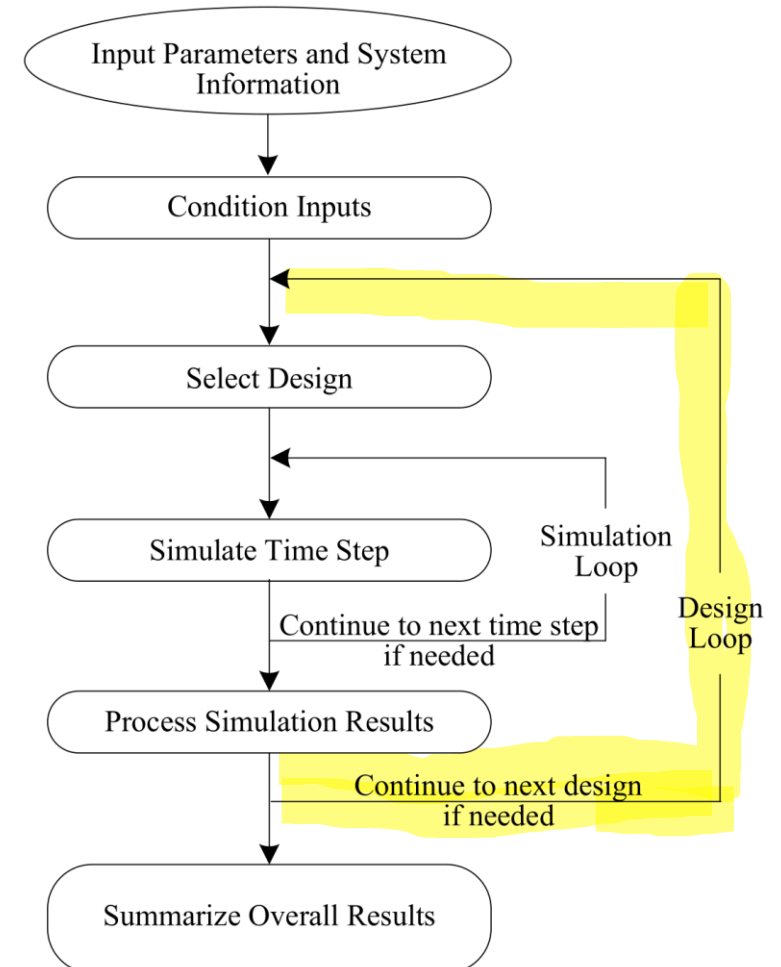
Numerical Design Algorithm

- Simulate several designs individually
 - advance through time at specified time step (e.g. hourly) for desired time period (e.g. one year)
 - process results (cost, reliability, etc.)
- Select next design to consider
- Compare results and the user selects the design for further design work



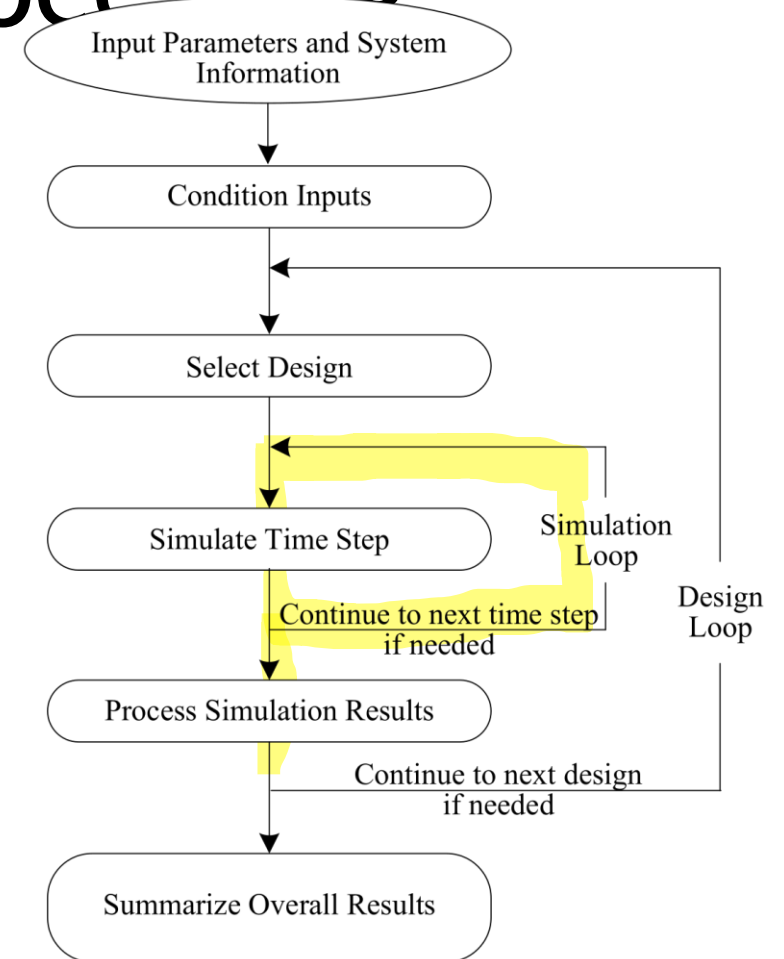
Design Loop

- Determines which combination of component sizes within the search space to simulate
- Example:
 - Inverter 8 kW
 - PV array: 36 kW
 - Battery bank: 55 kWh
 - Gen set: 15 kW



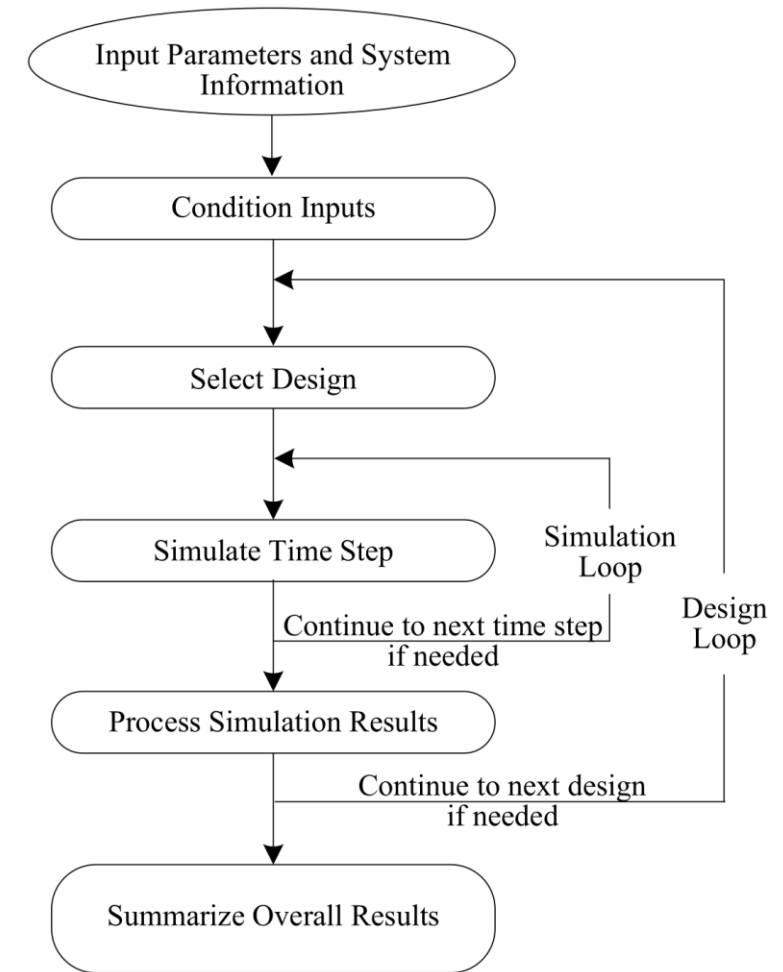
Simulation Loop & Results Processing

- Simulate system based on the sizes passed into it by the Design loop
- Process results to calculate:
 - operating costs
 - reliability
 - emissions
 - others of interest



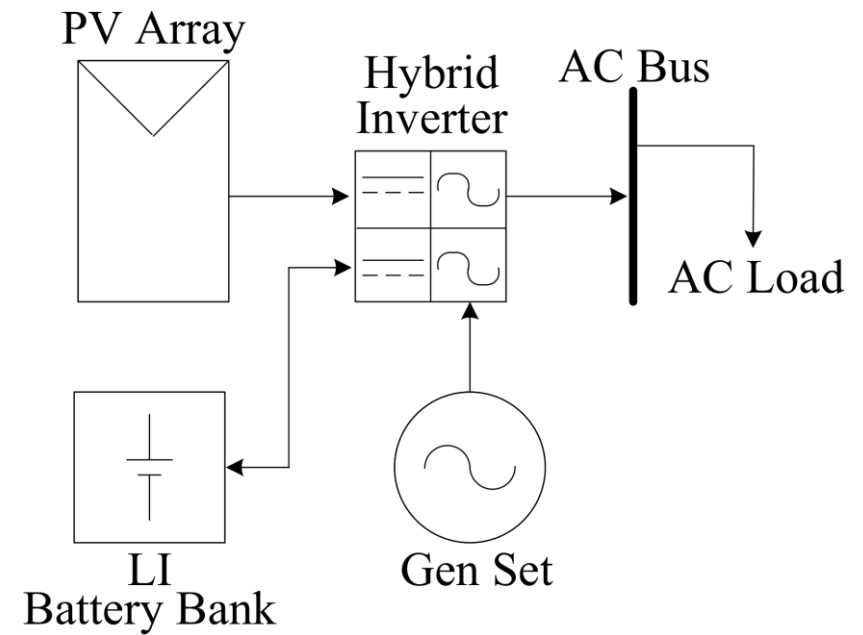
Results Interpretation

- After all designs have been considered, results are compared
- Further analyses:
 - search space might be changed (tightened or relaxed) and algorithm re-run
 - sensitivity: change one or more input parameters (such as load, fuel cost, irradiance) to see how results are affected
- Once design is selected, proceed to component selection and layout and final electrical design



Search Space Example

- Try several size combinations
- Setting a size to “0” removes that component from the architecture
- In practice 100s or 1000s of designs would be considered



	PV Array	Battery	Inverter	Gen Set
Design	S_{pv} kW	S_B kWh	S_{inv} kW	S_{gen} kW
A	22	45	10	7.5
B	22	45	10	0
C	32	68	10	0
D	30	40	12	7.5
E	14	50	12	7.5
F	34	80	18	7.5

Results Evaluation Example

Design	PV S_{PV} kW	Battery S_B kWh	Inverter S_{inv} kW	Gen Set S_{gen} kW	Capital Cost US\$	5-Year Fuel Cost US\$	Total Cost US\$	ENS kWh	ES %
A	22	45	10	7.5	49,275	14,963	64,238	1377	97
B	22	45	10	0	48,150	-	48,150	10148	78
C	32	68	10	0	68,200	-	68,200	1227	97
D	30	40	12	7.5	58,325	14,085	72,410	846	98
E	14	50	12	7.5	42,625	31,219	73,844	1745	96
F	34	80	18	7.5	80,725	203	80,928	0	100

Results Evaluation

reasonable
design

Design	PV S_{PV} kW	Battery S_B kWh	Inverter S_{inv} kW	Gen Set S_{gen} kW	Capital Cost US\$	5-Year Fuel Cost US\$	Yearly Total Cost US\$	ENS kWh	ES %
A	22	45	10	7.5	49,275	14,963	64,238	1377	97
B	22	45	10	0	48,150	-	48,150	10148	78
C	32	68	10	0	68,200	-	68,200	1227	97
D	30	40	12	7.5	58,325	14,085	72,410	846	98
E	14	50	12	7.5	42,625	31,219	73,844	1745	96
F	34	80	18	7.5	80,725	203	80,928	0	100

Results Evaluation

Design	PV S_{PV} kW	Battery S_B kWh	Inverter S_{inv} kW	Gen Set S_{gen} kW	Capital Cost US\$	5-Year Fuel Cost US\$	Yearly Total Cost US\$	ENS kWh	ES %
A	22	45	10	7.5	49,275	14,963	64,238	1377	97
B	22	45	10	0	48,150	-	48,150	10148	78
C	32	68	10	0	68,200	-	68,200	1227	97
D	30	40	Renewable energy only designs lower reliability or higher cost			35	72,410	846	98
E	14	50				9	73,844	1745	96
F	34	80	18	7.5	80,725	203	80,928	0	100

Results Evaluation

Design	PV S_{PV} kW	Battery S_B kWh	Inverter S_{inv} kW	Gen Set S_{gen} kW	Capital Cost US\$	5-Year Fuel Cost US\$	Yearly Total Cost US\$	ENS kWh	ES %
A	22	45	Design D: large PV, small battery Design E: large battery, small PV Both have higher costs than Design A				64,238	1377	97
B	22	45					48,150	10148	78
C	32	68					68,200	1227	97
D	30	40	12	7.5	58,325	14,085	72,410	846	98
E	14	50	12	7.5	42,625	31,219	73,844	1745	96
F	34	80	18	7.5	80,725	203	80,928	0	100

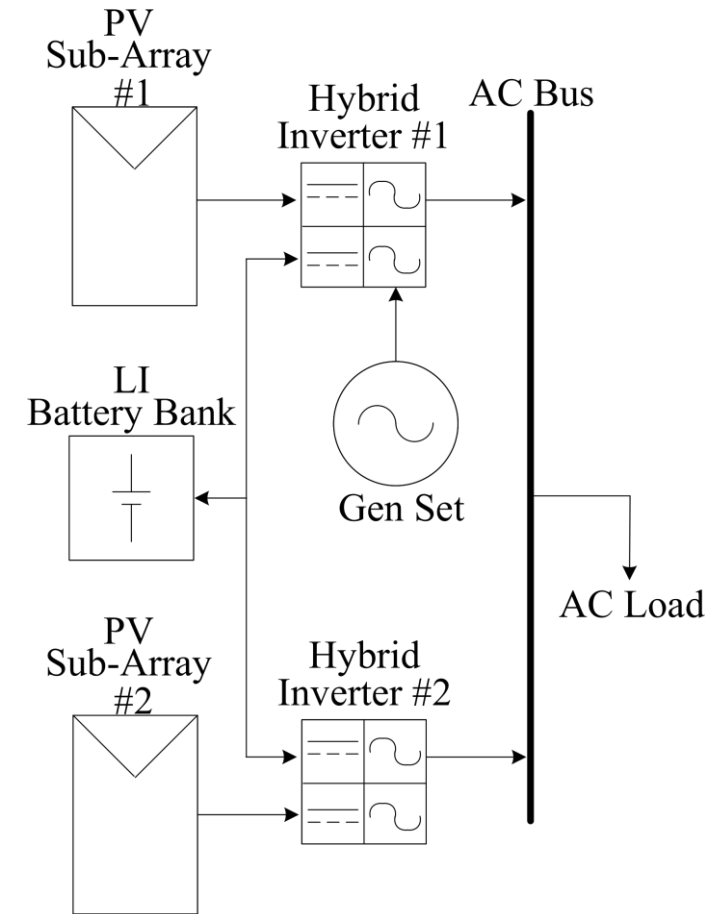
Results Evaluation

Design	PV S_{PV} kW	Battery S_B kWh	Inverter S_{inv} kW	Gen Set S_{gen} kW	Capital Cost US\$	5-Year Fuel Cost US\$	Yearly Total Cost US\$	ENS kWh	ES %
A	22	45	10	7.5	49,275	14,963	64,238	1377	97
B	22	45	10	0	48,150	-	48,150	10148	78
C	32	68	10	0	68,200	-	68,200	1227	97
D	30	40	12	7.5	58,325	14,085	72,410	846	98
E	14	50	10	7.5	58,325	14,085	72,410	846	98
F	34	80	18	7.5	80,725	203	80,928	0	100

Highest reliability, significantly higher cost

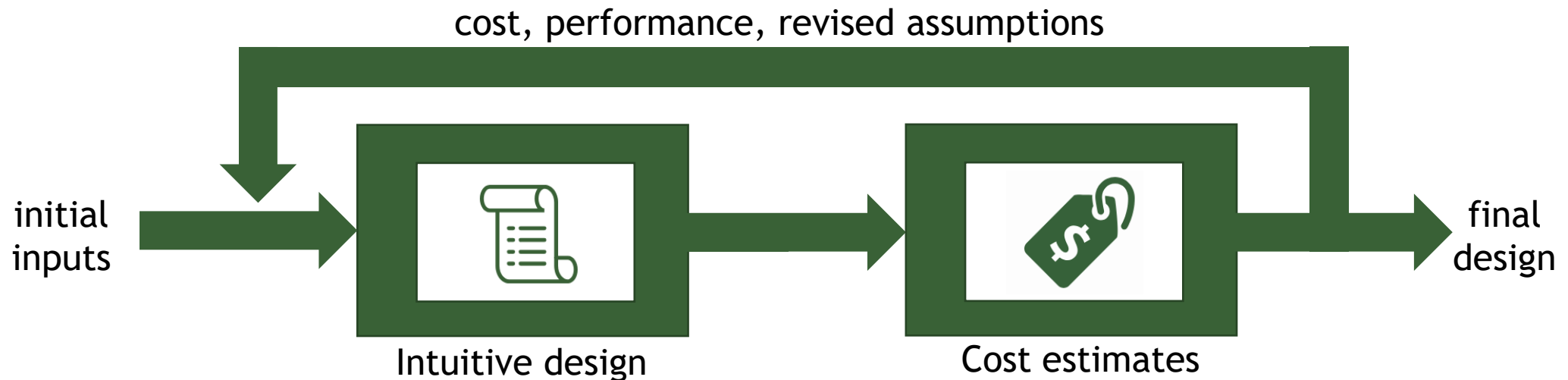
System Design

- After design is chosen, the specific components are selected as in an intuitive design process



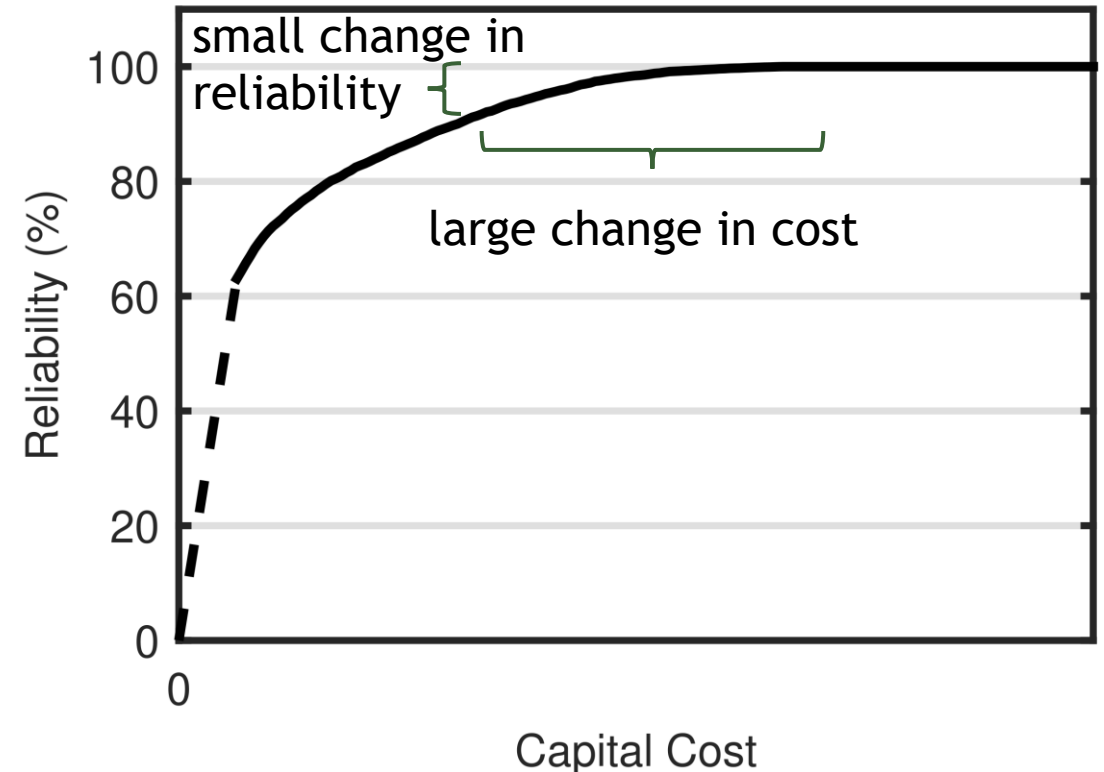
Iterative Design

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



Cost and Reliability Trade-off

- Increasing reliability of system can be accomplished by increasing generation source and/or energy storage capacity
- Costs often rapidly increase for small improvements in reliability
- Tradeoff: which is preferred, a more reliable system or a less expensive system
 - is it better to serve fewer people with highly reliable electricity or many more people with somewhat less reliable electricity?



Hybrid Mini-Grid Design

- PV/gen set hybrid mini-grids usually offer the best performance (lowest levelized cost of energy)
- Typical design ratios of major components
- For every 1 kW of PV capacity, there is approximately
 - 3-5 kWh of load served
 - 3-4 kWh lead-acid energy storage (or 1-3 kWh of lithium-ion)
 - 0.3 to 0.65 kWh of gen set capacity, which supplies 10-25% of load

Summary

- Promising community characteristics for mini-grids include: high population density, desire for electricity, ability to pay, among others
- Off-grid system design is an iterative process, involving balancing several tradeoffs between cost and capability
- Intuitive design: guided by standards or best practices, require limited information and assumptions about the load and energy resources
- Numerical design: computer simulation of different component sizes, providing summary of performance and cost

Module C: Off-Grid Distribution System Design

Off-Grid Electrical Systems in Developing Countries, 2nd Edition
Chapter 17



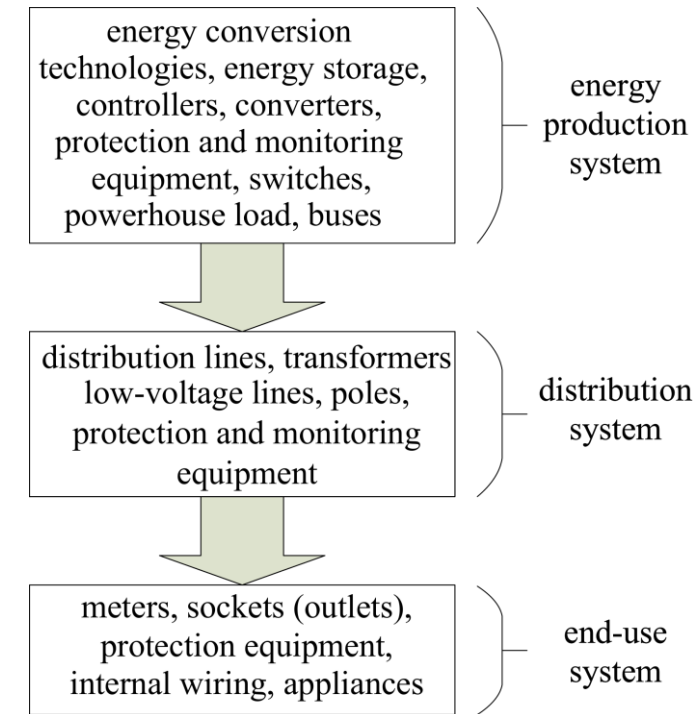
Learning Outcomes

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

- ✓ Compare and contrast different distribution system voltage types methods, topologies, and configurations
- ✓ Describe considerations and approaches to routing power lines in off-grid communities
- ✓ Perform engineering calculations for distribution systems including determining the voltage drop and power loss along distribution lines

Introduction

- Distribution systems facilitate the flow of power from energy production system to end-use system
- Mini-grids, metro-grids, and mesh/swarm grids have a distribution (“reticulation”) system
 - focus on mini-grid distribution system
 - low-voltage wires (typically <415 V)
 - usually less than 1 km in length



approximate “reach” of a
low-voltage distribution system
(1 km)



Satellite image Source: Google Earth, data attribution: Airbus/CNES

Distribution System Characteristics

Voltage Type: AC or DC

Method: overhead or underground

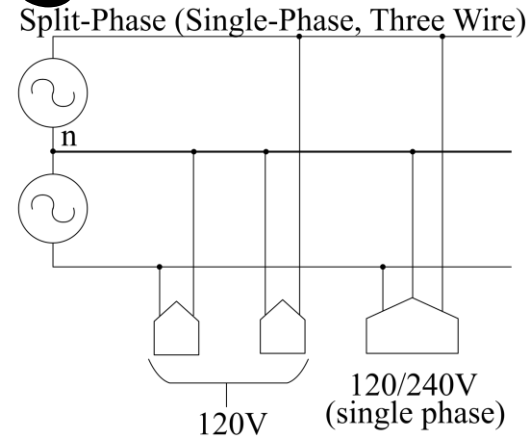
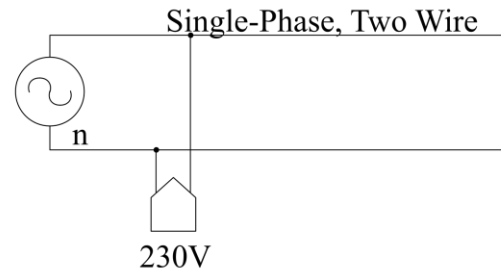
Topology: hub-and-spoke or trunk-and-branch

Configuration: single-phase, split-phase, or three-phase

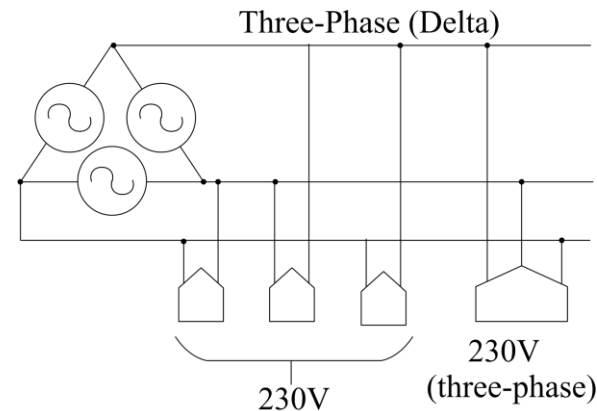
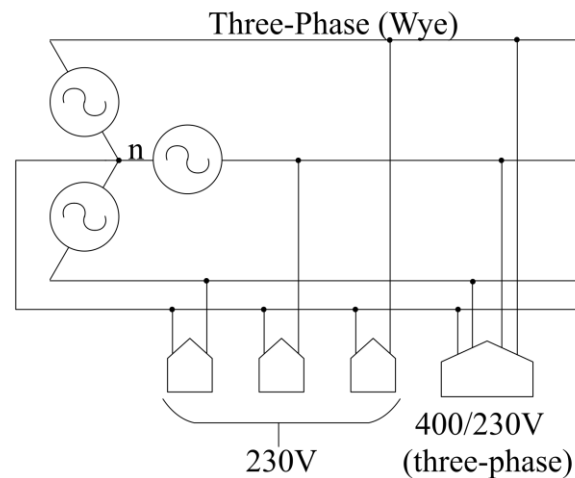
Advantages of AC Distribution

- ✓ Maturity of technology
- ✓ Availability of components (including load appliances)
- ✓ Capability for voltage transformation (step-up, step-down transformers)
- ✓ Compatibility with rotating machines (pumps, motors)
- ✓ Existing standards and codes (installers are more familiar with AC codes)

AC Distribution Configurations



split-phase is not common outside North/South America



Three-Phase

- Higher-capacity systems may use three-phase distribution
 - three-phase inverter (or three single-phase inverters connected together)
 - three-phase gen set
- Industrial and agricultural users may require three-phase service
 - pumps, motors, large loads
- Two configurations: delta, wye

Distribution Line Design Considerations

Thermal Limit

- Resistance causes distribution line to heat due to current (power) within it
- Overheating can cause failure
- Heating is inefficient (losses)
- Larger conductors reduce power loss

Distribution Line Design Considerations

Voltage Drop Limit

- Impedance causes a reduction in voltage along distribution line
- Voltage drop increases with current (power) flow
- Limit voltage drop to less than 5-10%
- Larger conductors reduce voltage drop

Real World Conditions

- Load typically not lumped at end of distribution line
 - lower losses and voltage drop if load is spread across line and closer to the sending end
- Load imbalance
 - aside from three-phase loads, loads will be imbalanced (homes will not consume the same load at each moment)
 - imbalance causes more current in neutral conductor and for uneven voltage at homes
 - losses and voltage drop can increase

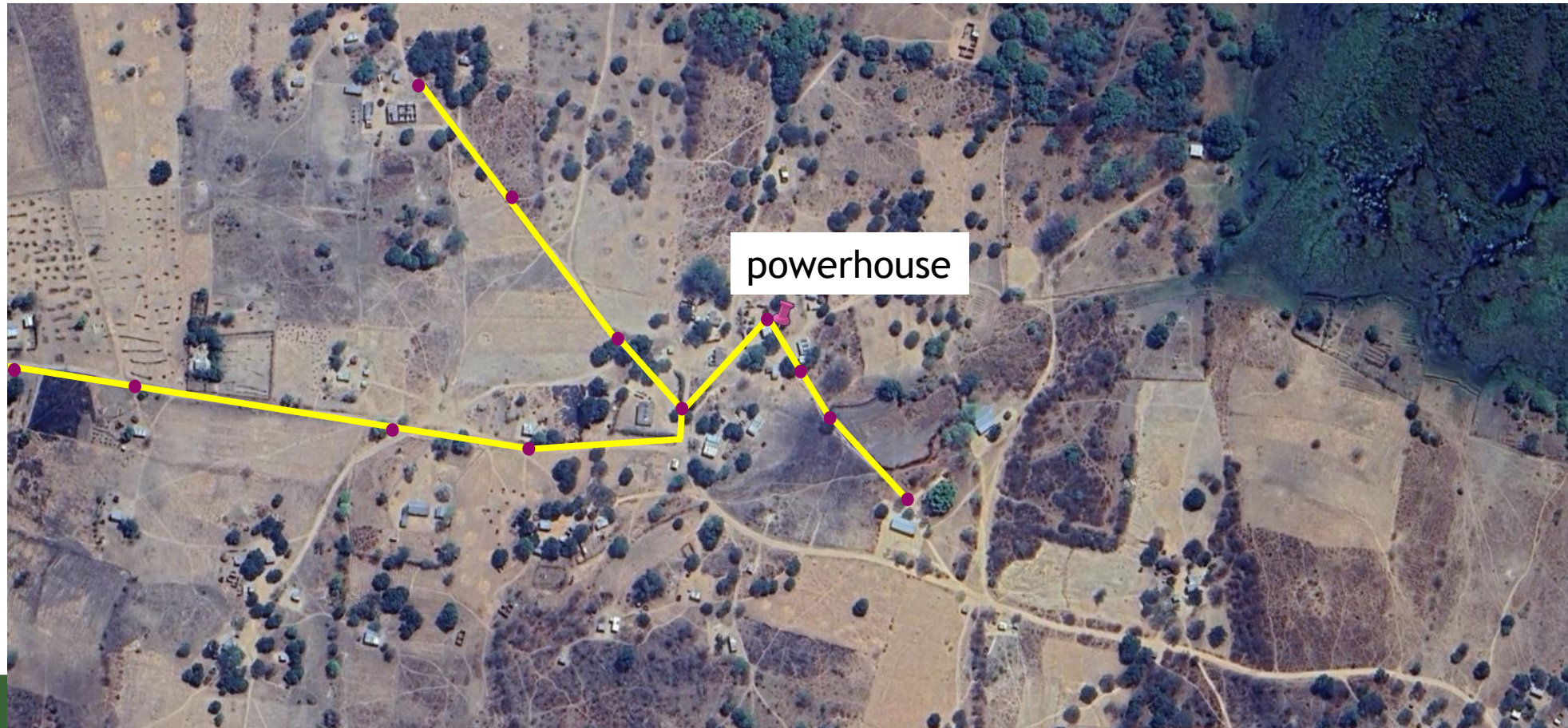
Distribution Design

- Design of distribution system includes selecting
 - voltage level and type (AC/DC)
 - method (overhead or underground)
 - topology (hub-and-spoke, trunk-and-branch, etc.)
 - configuration (single, split, three-phase)
- Conductor selection
- Distribution line routing

Distribution Line Routing

- Determine where lines are to be constructed
 - identify location for poles and transformers (if needed)
 - minimize total material cost (length of line)
- General strategy: locate lines along roads to minimize obstruction and to facilitate maintenance
- Calculate voltage drop and power loss of proposed design, re-design if necessary
 - software such as Xendee is commonly used

Distribution Line Routing



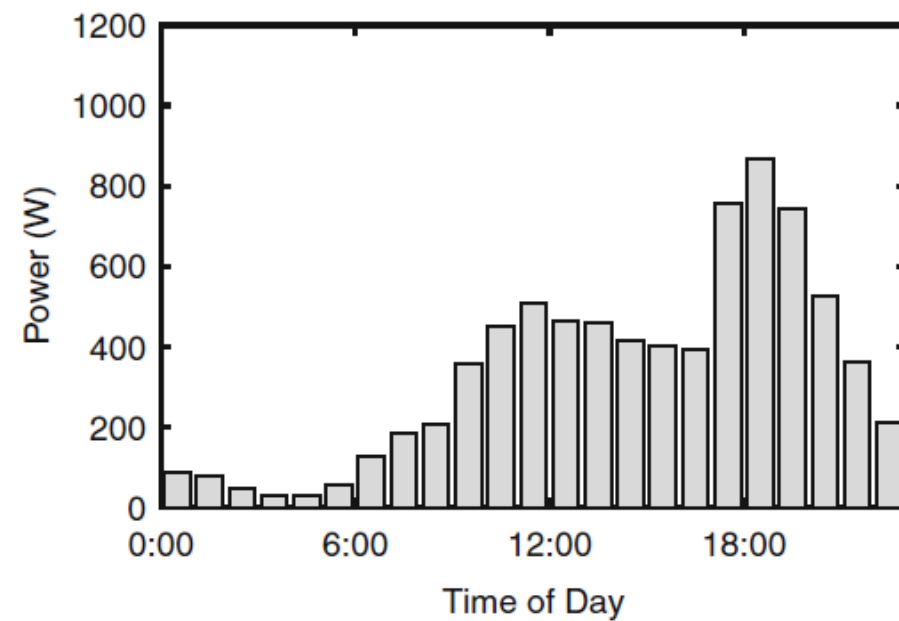
Satellite image Source: Google Earth, data attribution: Airbus



Distribution Design Example: Mwase

Load Estimation & Characterization (see Chap. 16)

- 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

Distribution Design Example

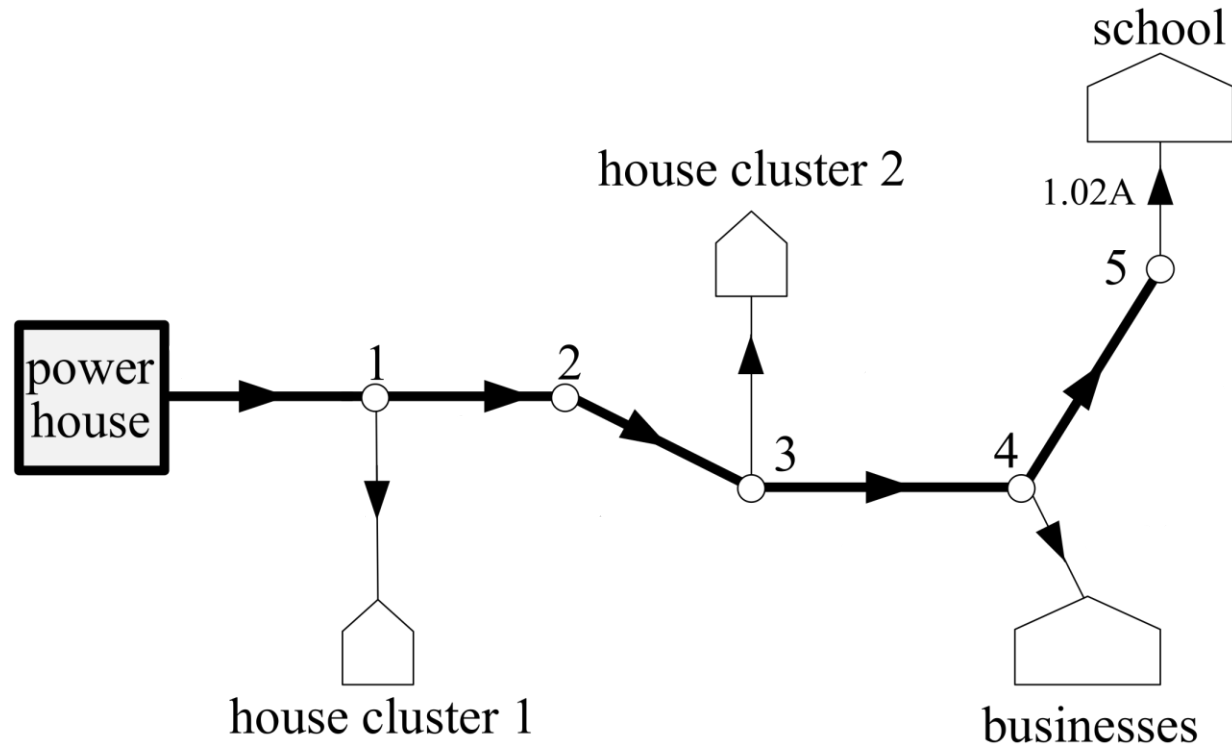
- Voltage level and type: 230 VAC
- Method: overhead
- Topology: radial (trunk-and-branch)
- Configuration: single-phase two wire

Distribution Design Conductor

Conductor: uninsulated ACSR (aluminum conductor, steel reinforced), 0.3 m spacing

Cross-sectional (mm ²)	Resistance (Ohm/km)	Reactance (Ohm/km)	Ampacity
13	2.25	0.31	105

Distribution Design: Routing



Voltage Drop and Loss Analysis

- Software often used
- Important to understand basic approach and calculations using as manual (and simplified) approach
- Compute voltage drop and losses based on peak load at each node
- Assumptions
 - nominal voltage (230 V) at each node
 - power factor is the same at each node (0.85)

1. Estimate Load Current at each node

$$|I_{L,n}| = \frac{P_{L,n}}{PF_{L,n} \times |V_s|} \quad |I_{L,1}| = \frac{200}{0.85 \times |230|} = 1.02 \text{ A}$$

Node	Length (km)	Estimated Coincident Peak Load (W)	Estimated Load Current $ I_{L,n} $	Segment $ Z_{w,s} $ (Ω)	Segment $ I_s $ (A)	Segment Voltage Drop (V)	Segment Power Loss (W)
5	0.15	200	1.02				
4	0.10	1300	6.65				
3	0.08	100	0.51				
2	0.05	0	0				
1	0.05	300	1.53				

Totals

2. Calculate the line segment impedance magnitude

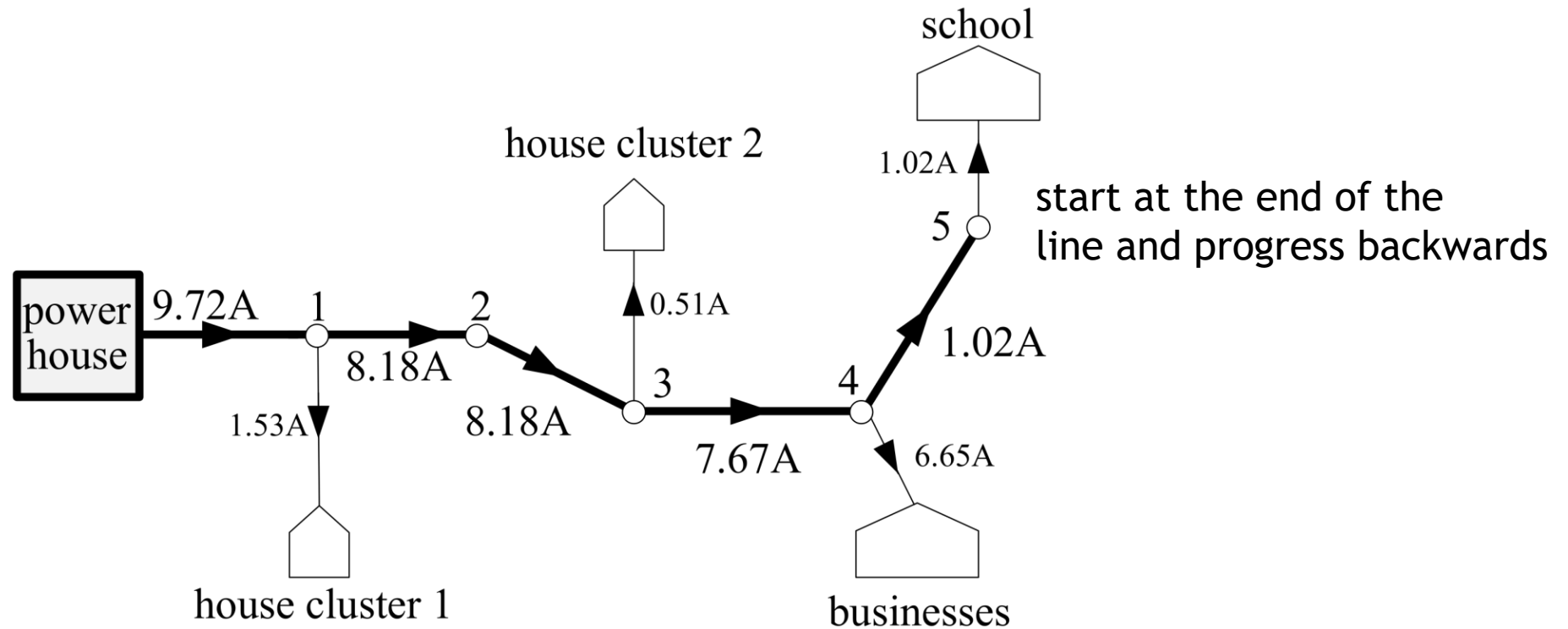
line impedance: $2.25 + j0.31$ Ohms/km

$$\sqrt{(2.25 \times 0.15)^2 + (0.31 \times 0.15)^2} = 0.341 \text{ m}$$

Node	Length (km)	Estimated Coincident Peak Load (W)	Estimated Load Current $ I_{L,n} $	Segment $ Z_{w,s} $ (Ω)	Segment $ I_s $ (A)	Segment Voltage Drop (V)	Segment Power Loss (W)
5	0.15	200	1.02	0.341			
4	0.10	1300	6.65	0.227			
3	0.08	100	0.51	0.182			
2	0.05	0	0	0.114			
1	0.05	300	1.53	0.114			

Totals

3. Calculate line segment current via KCL at each node



3. Calculate line segment current via KCL at each node

Node	Length (km)	Estimated Coincident Peak Load (W)	Estimated Load Current $ I_{L,n} $	Segment $ Z_{w,s} $ (Ω)	Segment $ I_s $ (A)	Segment Voltage Drop (V)	Segment Power Loss (W)
5	0.15	200	1.02	0.341	1.02		
4	0.10	1300	6.65	0.227	7.67		
3	0.08	100	0.51	0.182	8.18		
2	0.05	0	0	0.114	8.18		
1	0.05	300	1.53	0.114	9.72		

Totals

4. Calculate the voltage drop at each segment

use the voltage drop equation that corresponds to the distribution configuration

$$V_{\text{drop}} = 2 |I_L| H |Z_w| = 2 |1.02| 1 |0.341| = 0.70 \text{ V}$$

loads have been lumped together at each node, so let $H = 1$

Node	Length (km)	Estimated Coincident Peak Load (W)	Estimated Load Current $ I_{L,n} $	Segment $ Z_{w,s} $ (Ω)	Segment $ I_s $ (A)	Segment Voltage Drop (V)	Segment Power Loss (W)
5	0.15	200	1.02	0.341	1.02	0.70	
4	0.10	1300	6.65	0.227	7.67	3.49	
3	0.08	100	0.51	0.182	8.18	2.97	
2	0.05	0	0	0.114	8.18	1.86	
1	0.05	300	1.53	0.114	9.72	2.21	

Totals 11.22

voltage drop at the end of the line

5. Calculate the power loss for each segment

$$P_{\text{Loss}} = 2(H |I_L|)^2 R_w = 2(1 \times 1.02)^2 (2.25 \times 0.15) = 0.71 \text{ W}$$

use the power loss equation that corresponds to the distribution configuration

loads have been lumped together at each node, so let $H = 1$

Node	Length (km)	Estimated Coincident Peak Load (W)	Estimated Load Current $ I_{L,n} $	Segment $ Z_{w,s} $ (Ω)	Segment $ I_s $ (A)	Segment Voltage Drop (V)	Segment Power Loss (W)
5	0.15	200	1.02	0.341	1.02	0.70	0.71
4	0.10	1300	6.65	0.227	7.67	3.49	26.49
3	0.08	100	0.51	0.182	8.18	2.97	24.11
2	0.05	0	0	0.114	8.18	1.86	15.07
1	0.05	300	1.53	0.114	9.72	2.21	21.25

Totals 11.22 87.63

total power loss

Distribution Line Example

If voltage drop or power loss is too large or if segment exceeds conductor ampacity, then re-design

- select larger conductor
- change configuration type
- increase voltage (careful not to exceed voltage maximum)
- change routing

Summary

- Distribution systems are important considerations for mini-grids, metro-grids, and mesh/swarm grids
- Design decisions: AC/DC, overhead/underground, topology, configuration (single, split, three-phase)
- Different configurations result in different voltage drop and losses (three-phase wye best use of conductors)
- Routing design includes specifying route for each line, poles, and transformers (if necessary)
- Simplified voltage drop and power loss calculation method presented

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