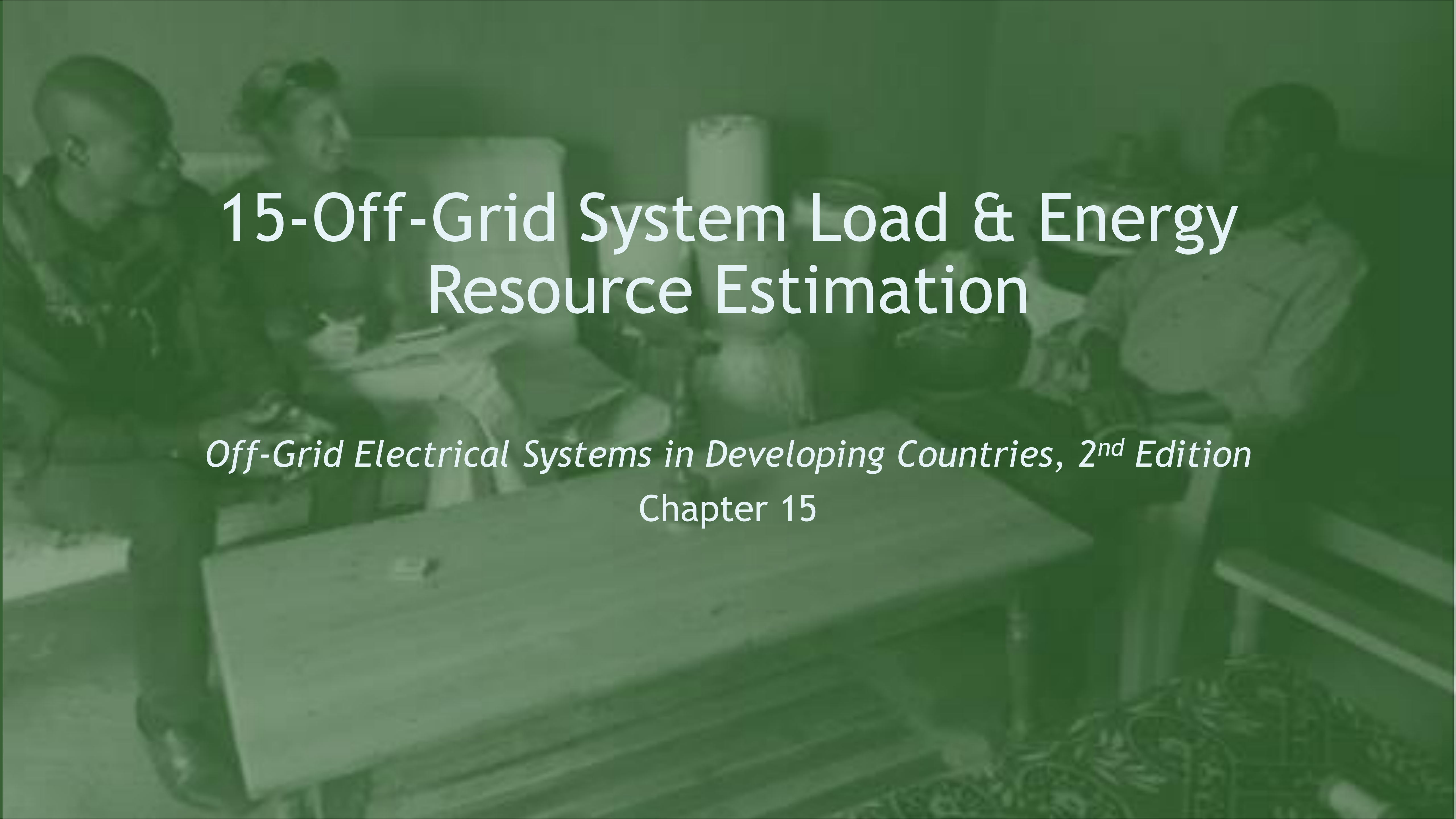


15-Off-Grid System Load & Energy Resource Estimation

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

Chapter 15

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries*, 2^{nd} *Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

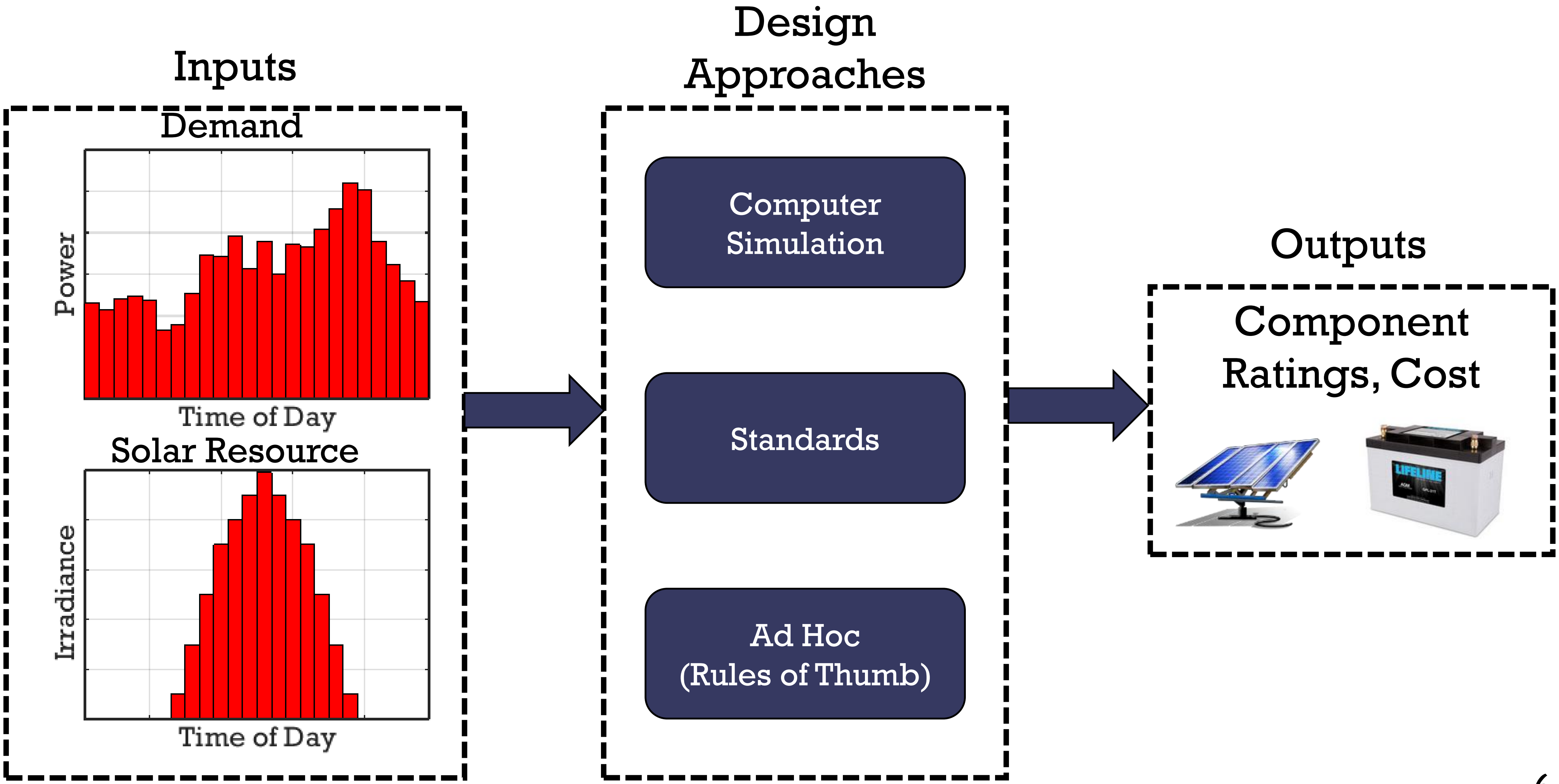
Learning Outcomes

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

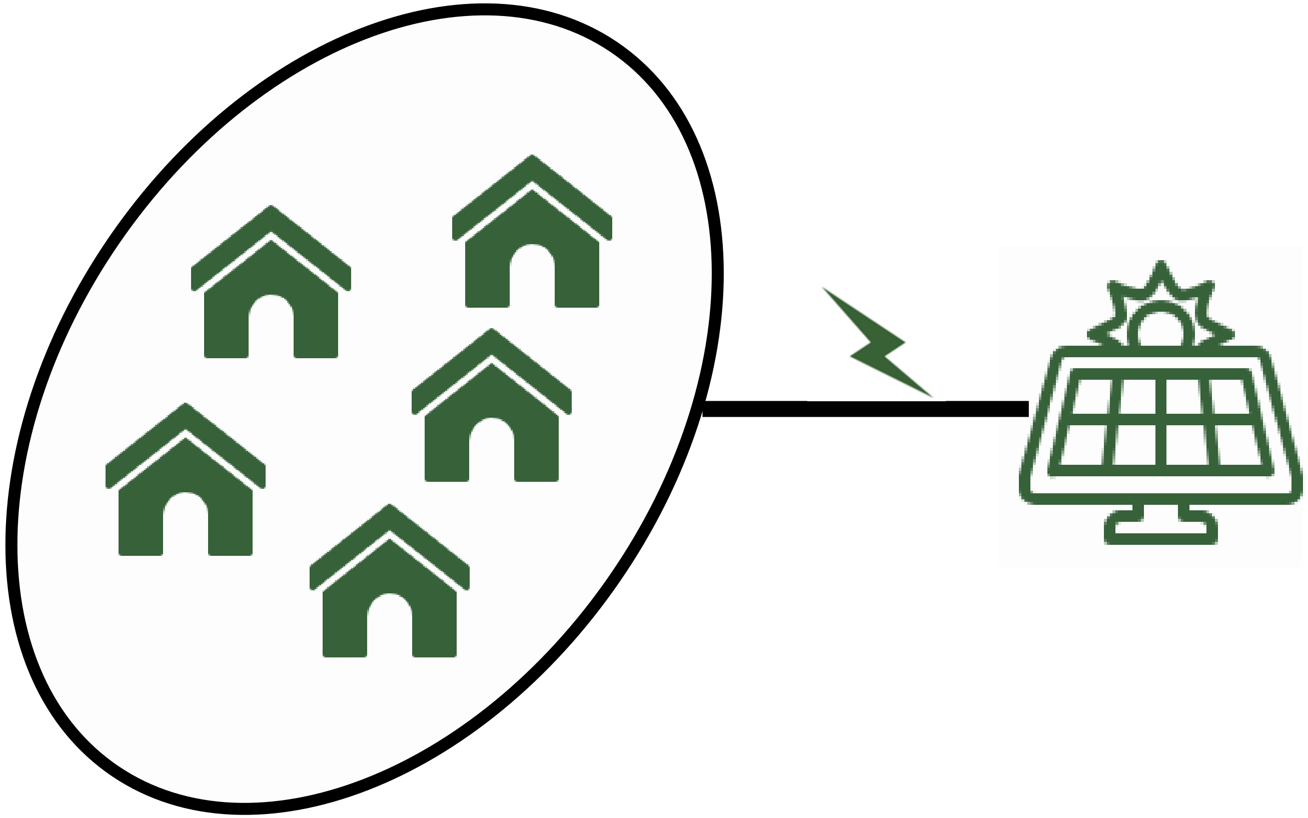
- ✓Explain the significance of accurate load and energy resource estimation in designing off-grid systems
- ✓Mathematically characterize off-grid system load by calculating the load profile, peak load, demand factor, load factor, and coincidence factor
- ✓Compare and contrast approaches to load estimation
- ✓Assess and mathematically model solar, wind, hydro, biomass, and fossil fuel energy resources
- ✓Calculate and evaluate different energy conversion technologies based on their capacity factor

Introduction

- Appropriately designed off-grid systems balance the cost of the system and 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 lecture


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

Load Characteristics



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

✓How much load (average daily load and peak)

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

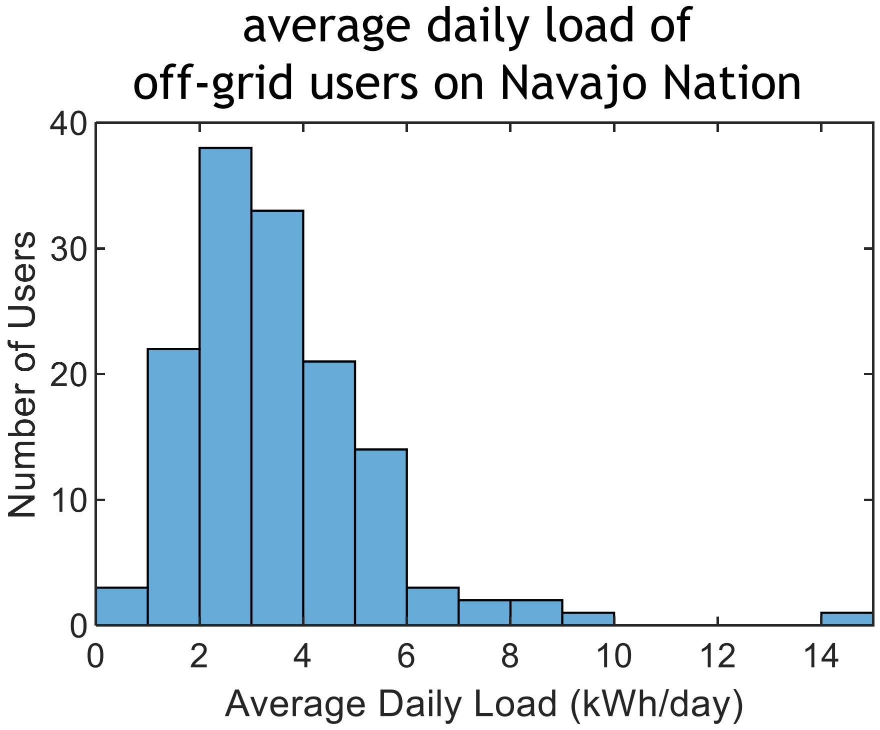
Representative Data

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)



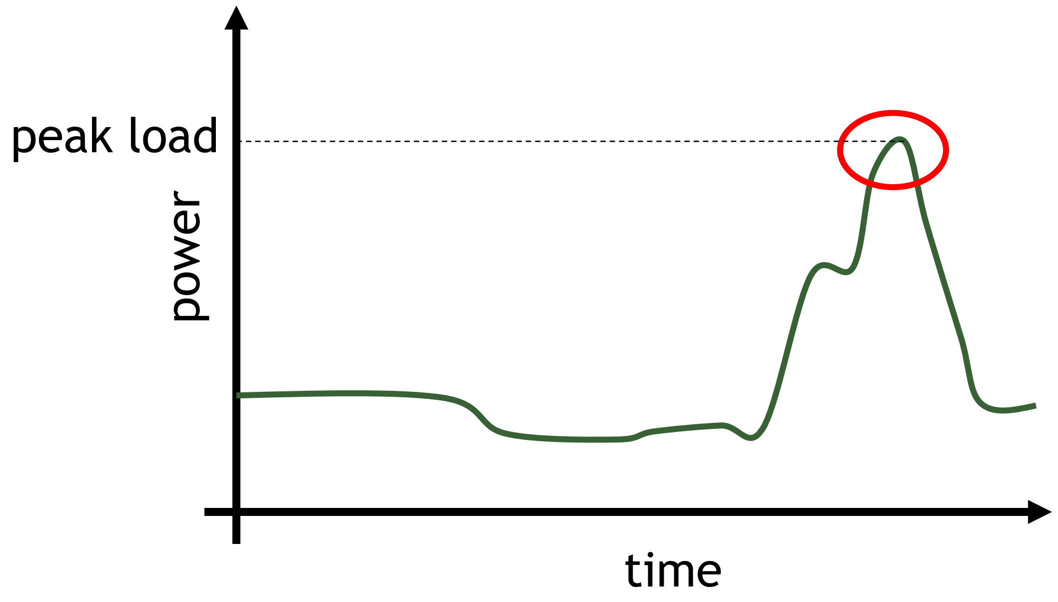
Average Daily Load

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

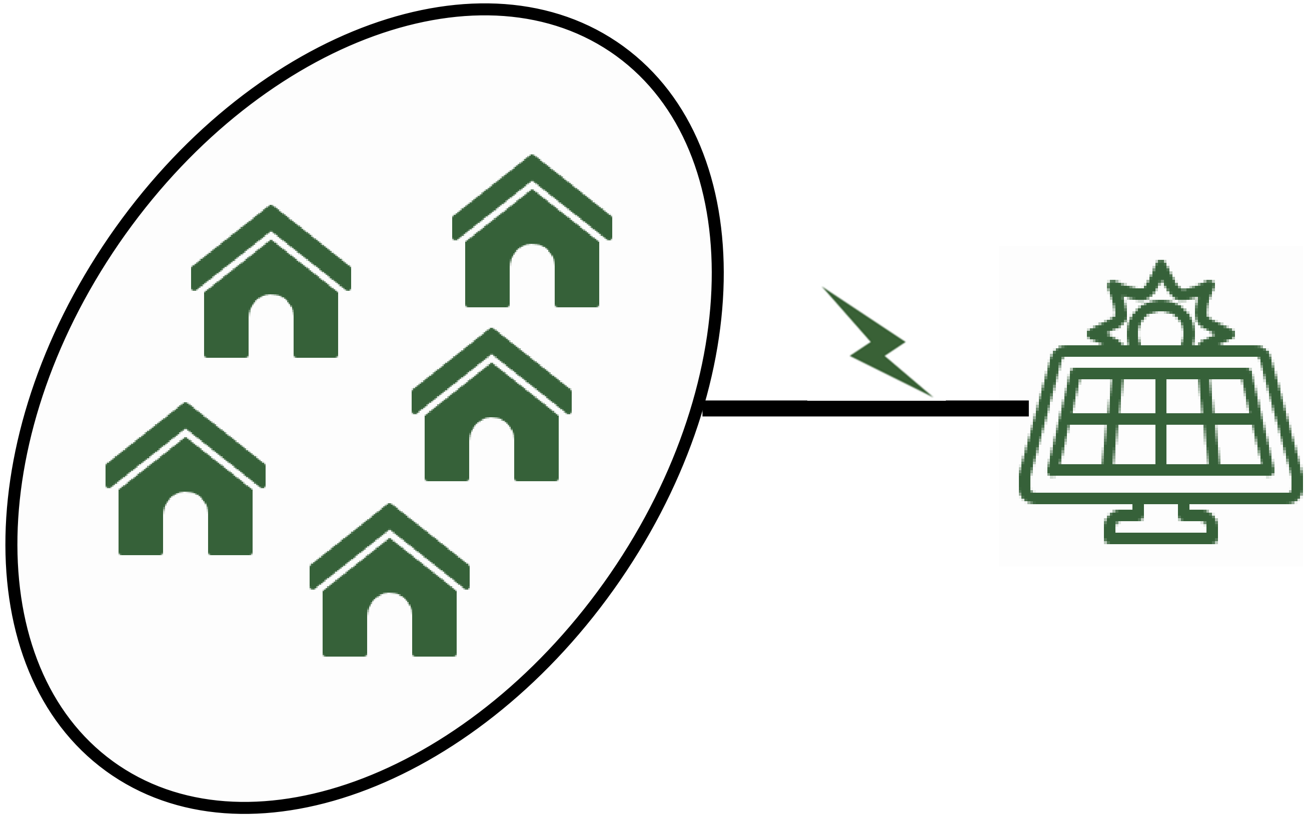
$\bar{E}$: Average daily load (kWh/day)
D: number of days

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 Characteristics

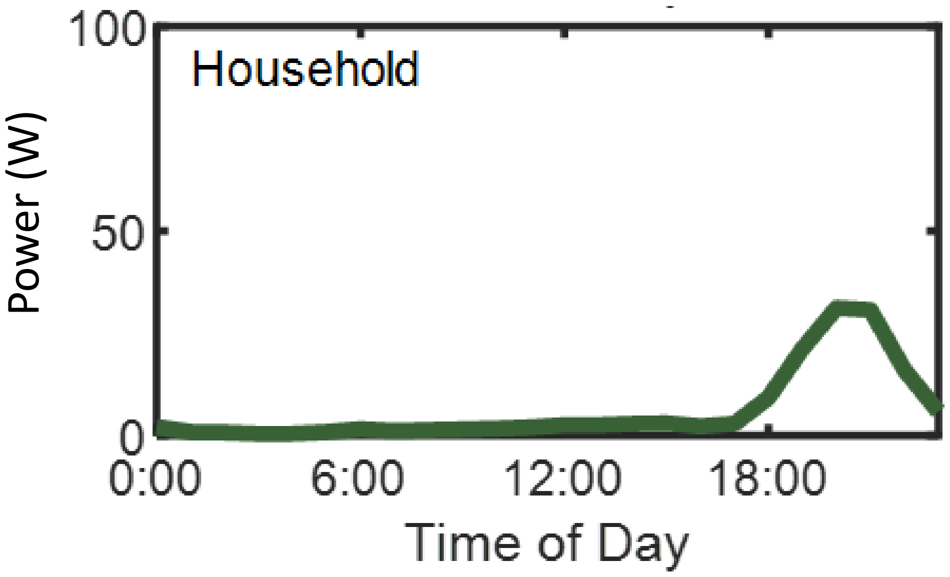


What do we need to know about the load to design our system?

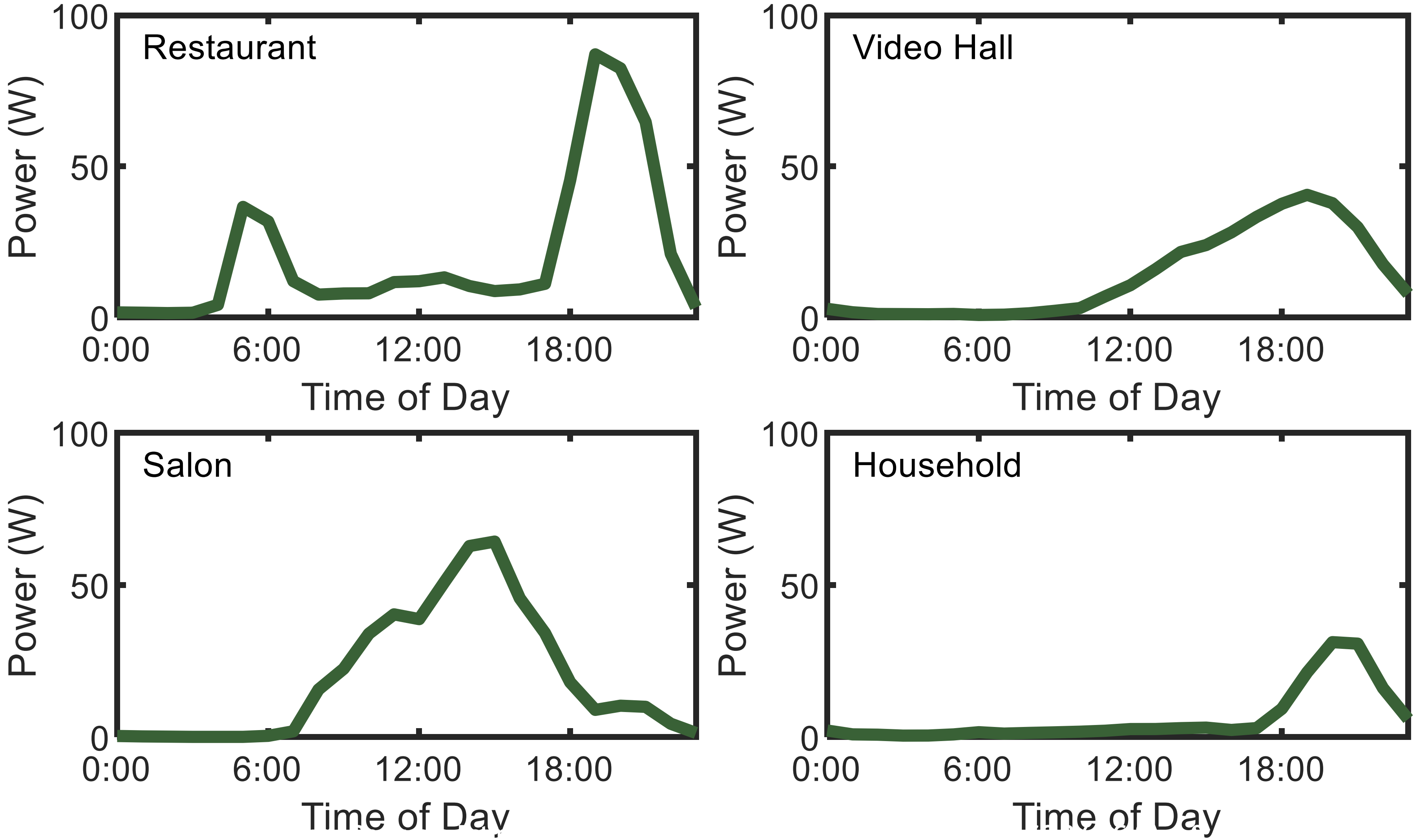
- ✓How much load (average daily load and peak)
- ✓When it is consumed (daily load profile)

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

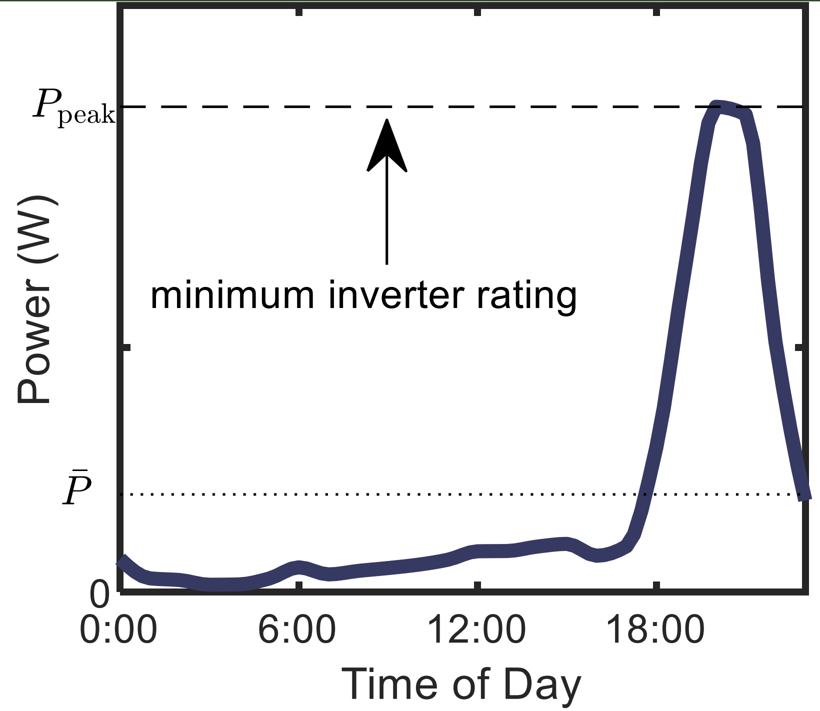


Load Factor (LF)

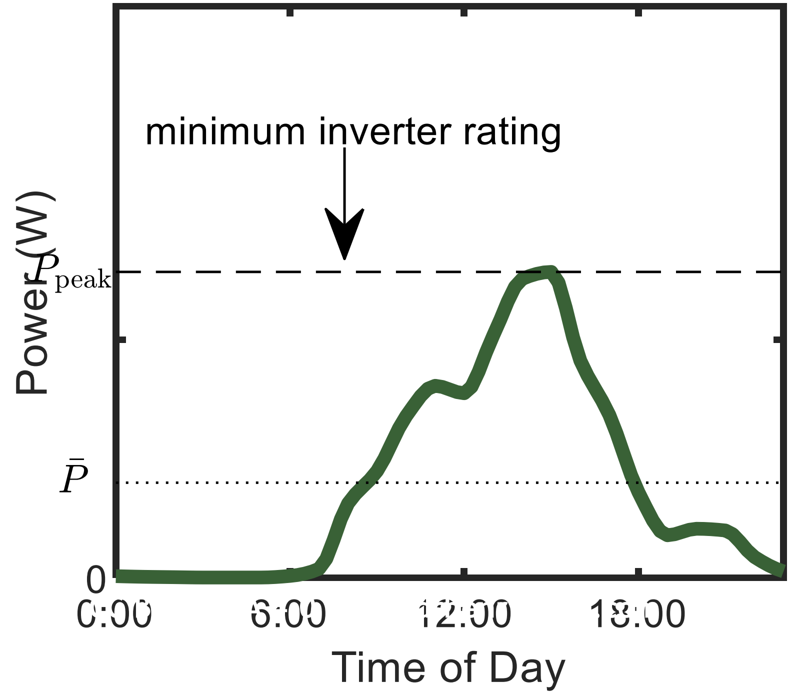
- Load Factor: *ratio of average power $\bar{P}$ and peak load P_{peak}*
- Higher load factors are desirable
  - lower equipment power ratings needed

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

low load factor (0.20)

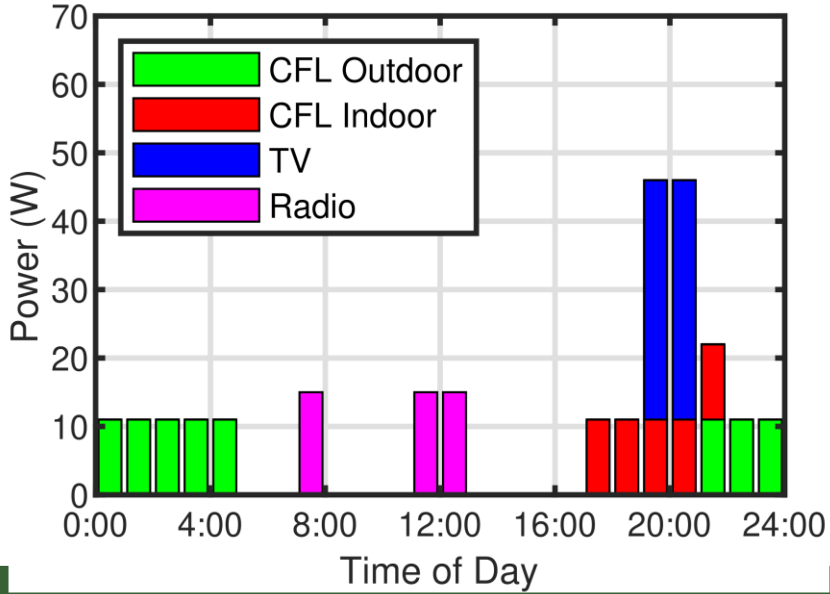


high load factor (0.31)



Example 15.2

Compute the average daily load, the peak load, the load factor, and the demand factor. Make the simplifying assumption that each appliance consumes exactly the rated power when turned on.



Appliance	Rating (W)
CFL	11
TV	35
Radio	15

Example 15.2

Average daily load:

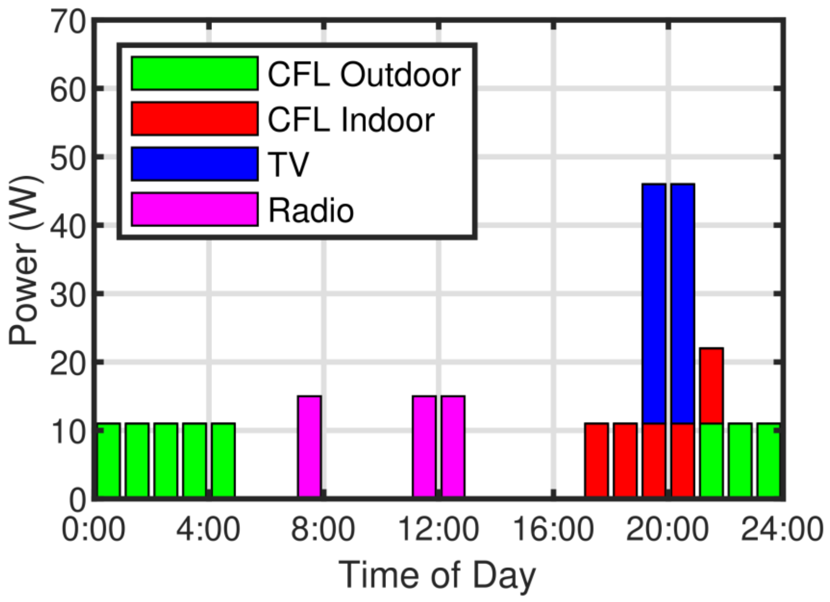
CFL outdoor: 8 x 11 = 88 Wh

CFL indoor: 5 x 11 =55 Wh

TV: 2 x 35 = 70 Wh

Radio: 15 x 3 = 45 Wh

Total: 258 Wh



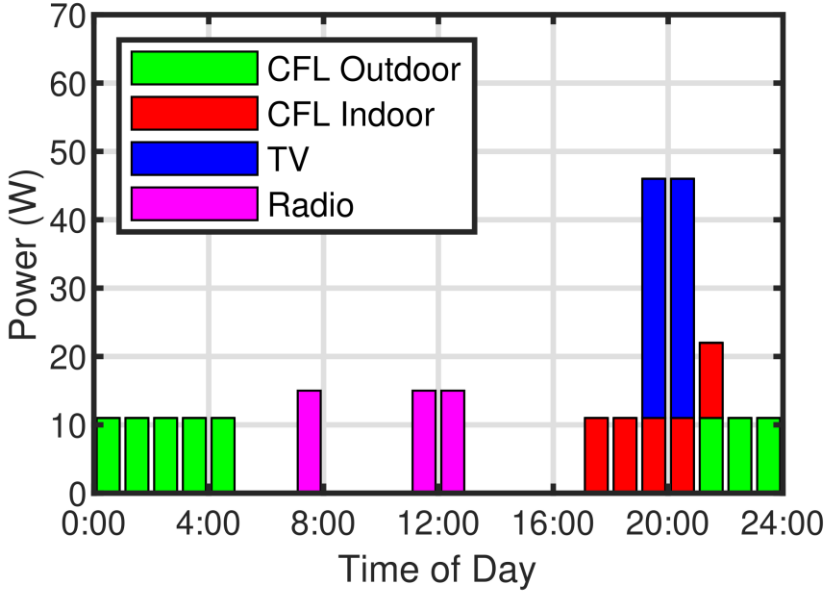
Appliance	Rating (W)
CFL	11
TV	35
Radio	15

Example 15.2

Peak: 35 + 11 = 46 W

$$LF = \frac{\bar{E}}{24 \times P_{\text{peak}}} = \frac{258}{24 \times 46} = 0.234$$

$$DF = \frac{P_{\text{peak}}}{\sum_{a=1}^{A} P_{a,\max}} = \frac{46}{11 + 11 + 15 + 35} = 0.639$$



Appliance	Rating (W)
CFL	11
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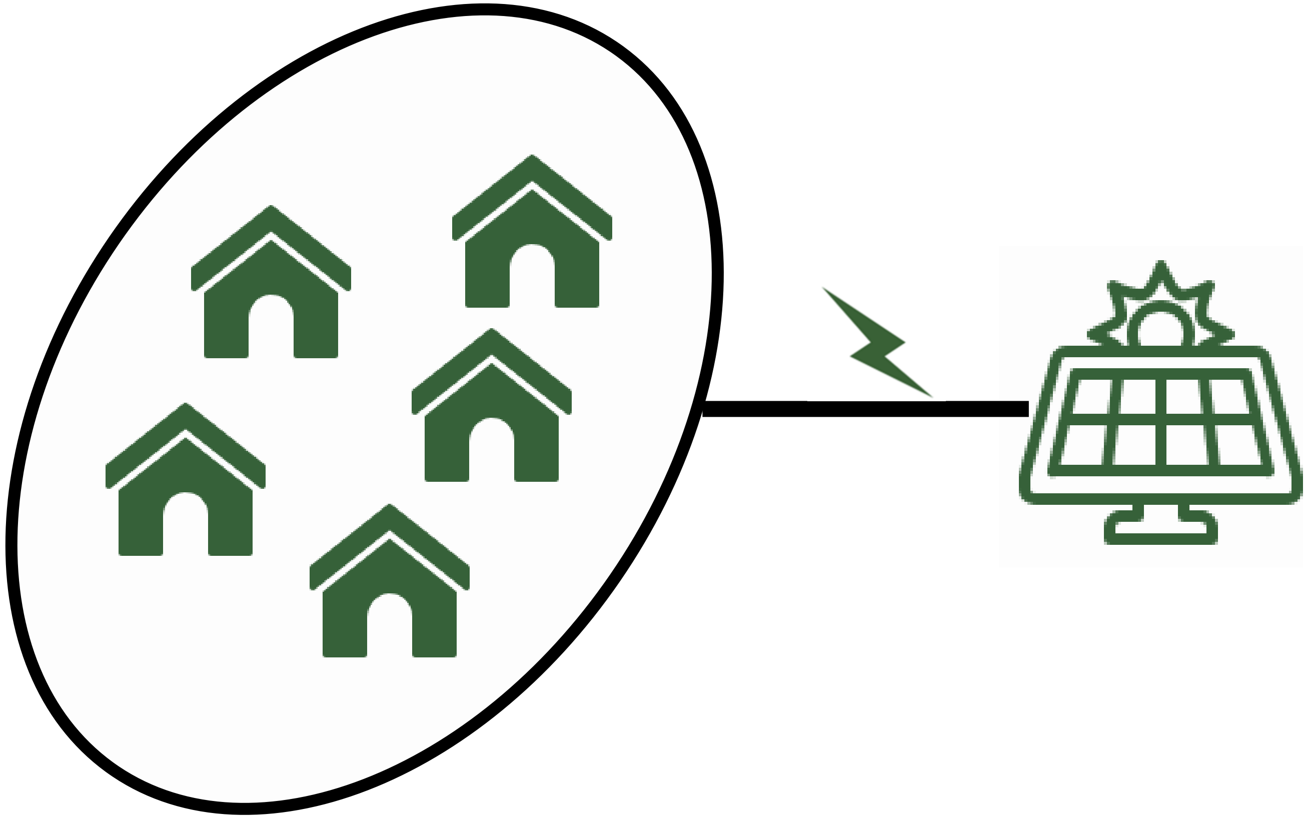
Load Characteristics

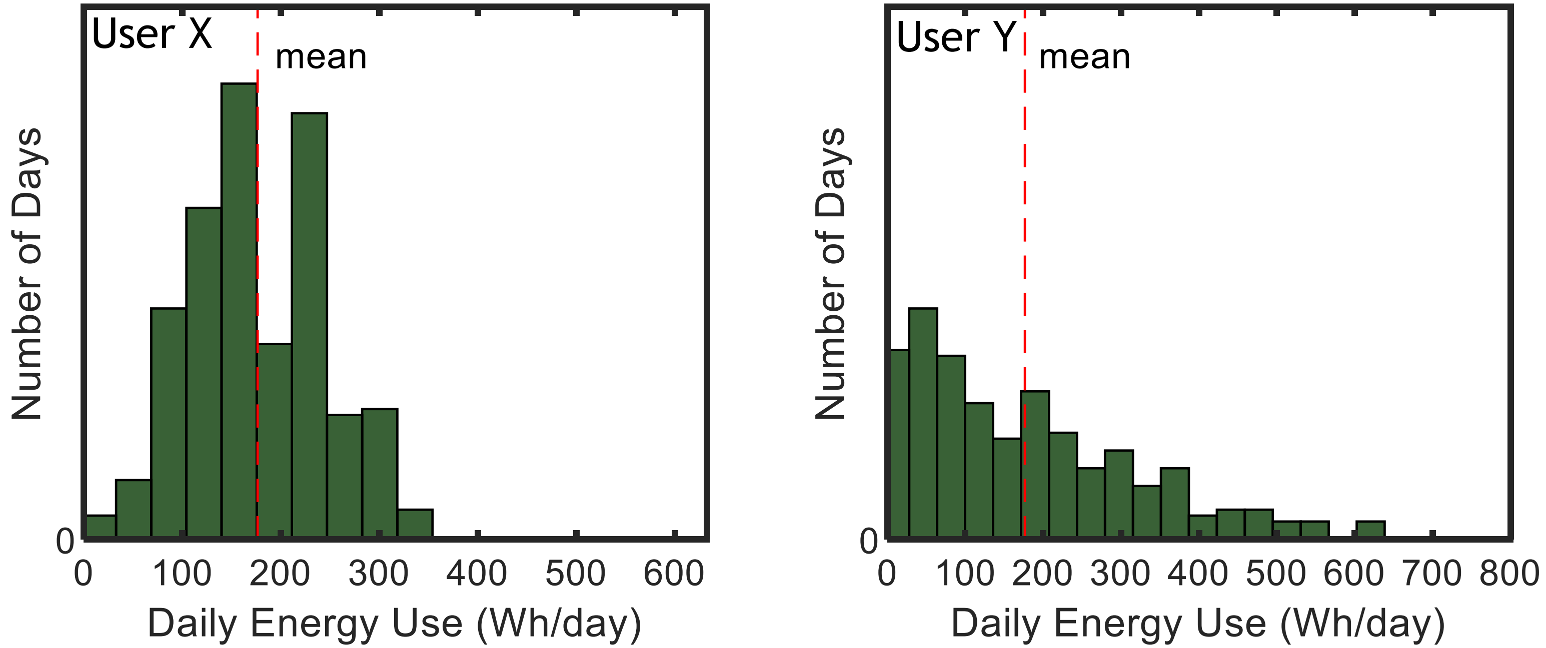


What do we need to know about the load to design our system?

- ✓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)

Day-to-Day Variation

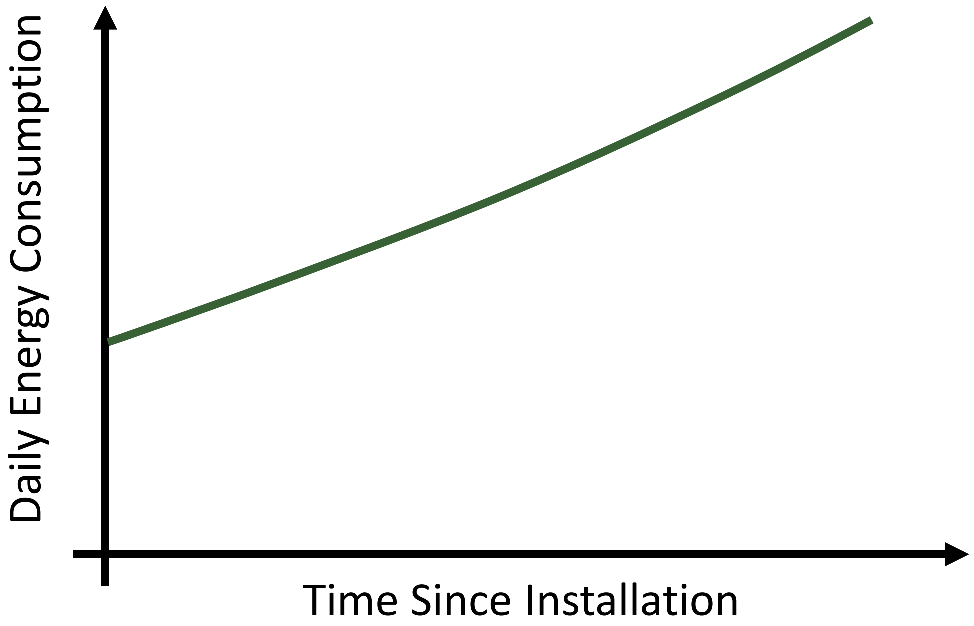
Reliability is dictated by extreme conditions, which is not captured by the average daily load



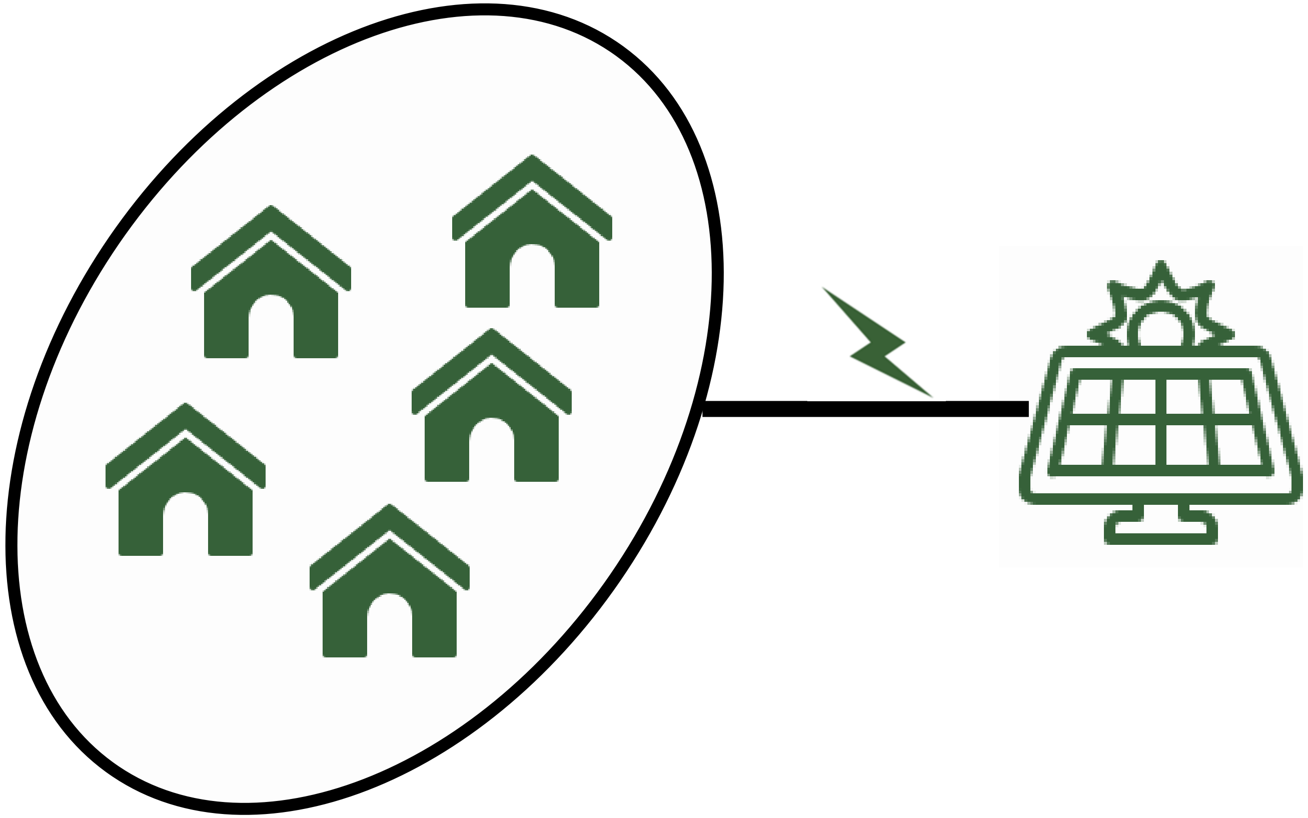
User X and Y have same average daily consumption, but User Y's consumption is more variable and requires a more expensive system to reliably serve

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 Characteristics

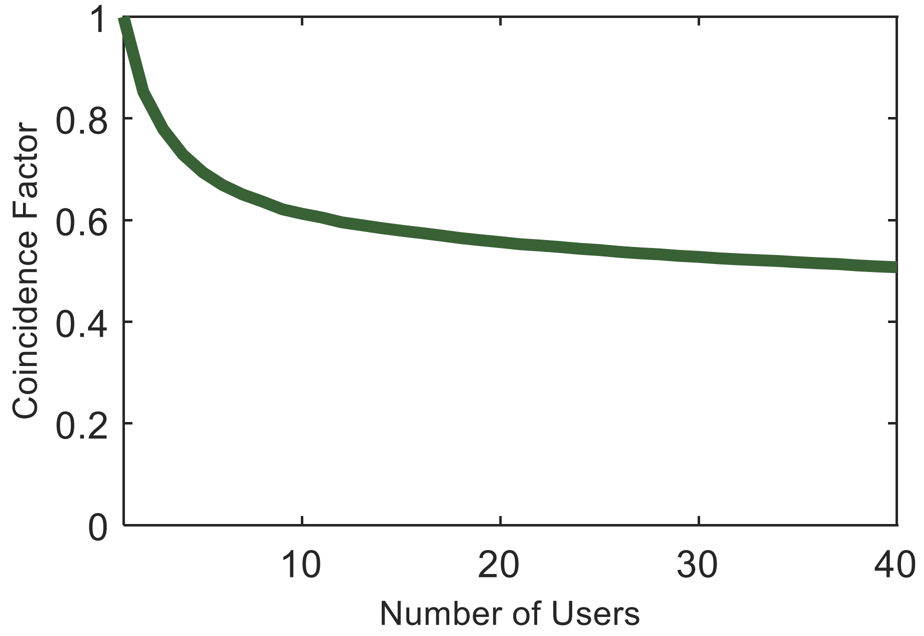


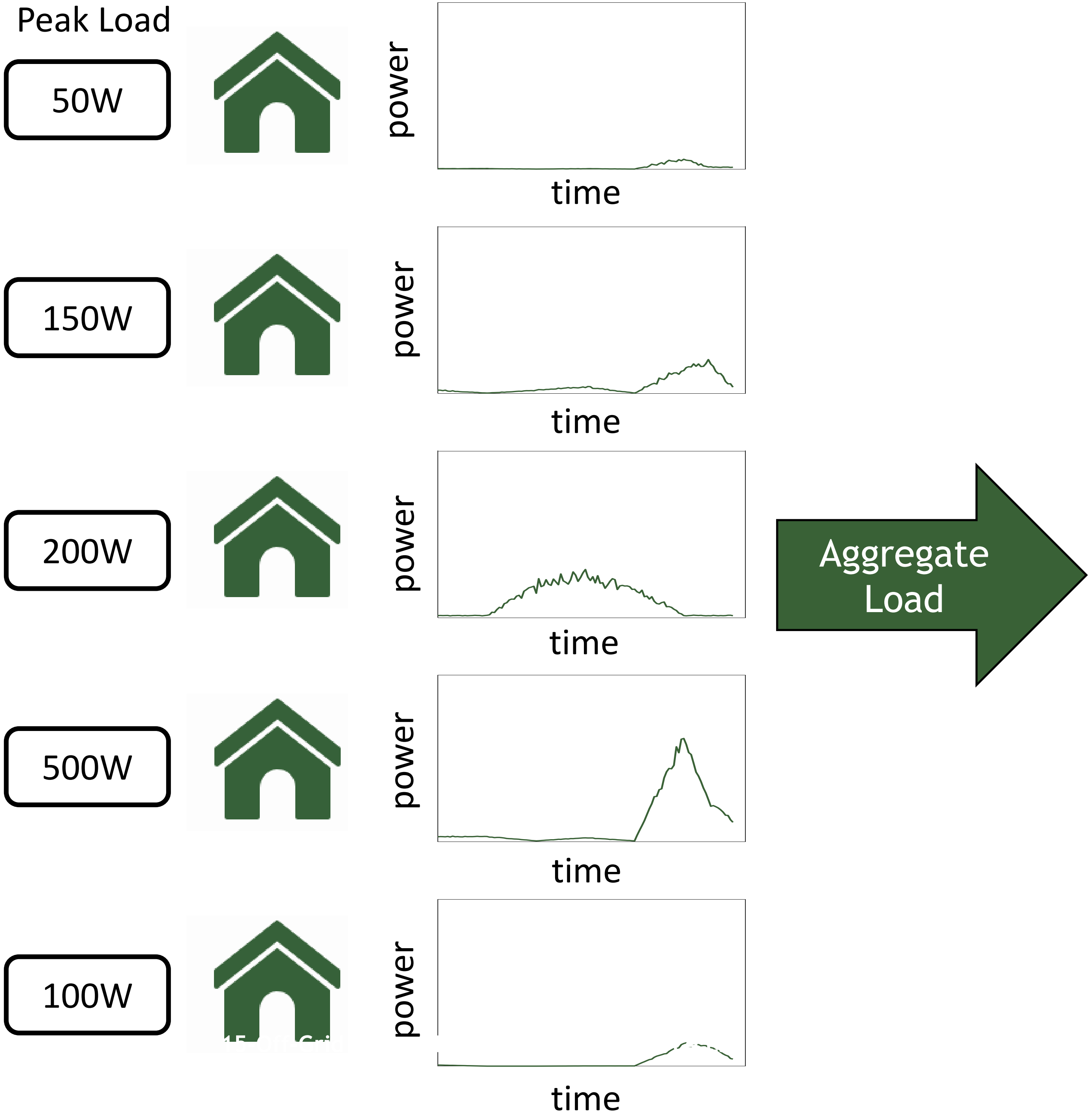
What do we need to know about the load to design our system?

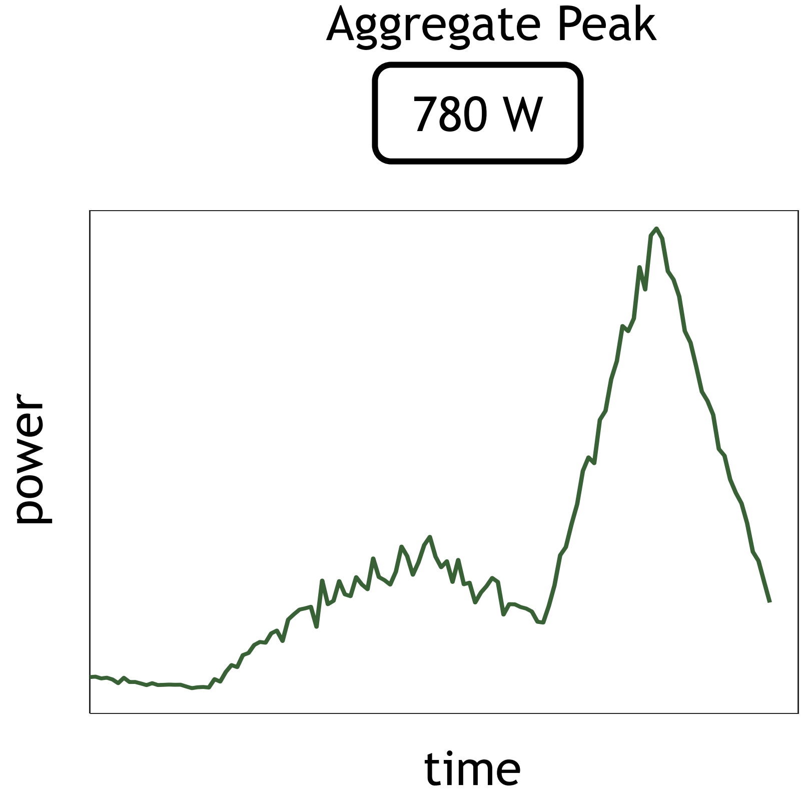
- ✓How much load (average daily load and peak)
- ✓When it is consumed (daily load profile)
- ✓How load varies over time (day-to-day and year-to-year)
- ✓How load is coincident between users

Coincidence Factor (CF)

- Coincidence Factor: *ratio of the peak aggregate load to the sum of the individual peak loads*
- Less coincidence is desirable
- Households tend to exhibit high coincidence
- Inverse of CF is known as the *diversity factor*







Serving many, diverse users reduces the aggregate peak, increases the Load Factor and lowers the day-to-day variation

Coincidence Factor

$$CF = \frac{P_{\text{peak,agg}}}{\sum_{n=1}^{N} P_{\text{peak},n}}$$

$P_{\text{peak,agg}}$: peak of the aggregate load (W)
$P_{\text{peak},n}$: peak of the *n*th user

Do not confuse "CF" for "Capacity Factor"
CF for a single user is 1.0

Preferable Load Characteristics

Characteristic	Description	Preferable Value
Average Daily Load	average load per day	large value
Load Profile	average load at each hour of the day	flat or coincident with energy resource availability
Peak Power	maximum power consumed by the load	small value
Load Factor	ratio of average load to the peak power	close to 1.0
Demand Factor	ratio of peak power to maximum possible power	low value
Coincidence Factor	ratio of peak aggregate load to sum of individual peak loads	low value
Diversity factor	inverse of the coincidence factor	high value
Load Variation	variation in daily load	low variation
Load Growth	how load increases with time	depends

Load Estimation Approaches

- Bottom-up
- Survey
- Regression
- 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

Example Appliance Ratings

Appliance	Rating (W)	Loading Percentage (%)
Blow Dryer	1369	100
CFL Bulb	11	100
Cooker	5000	varies
Desktop Computer	225	33
DVD Player	21	100
Fan	20	100
Freezer	19	100
Laptop Computer	60	40
LED Light	7	100
Phone Charger	3.7	100
Refrigerator	90	50
Television	35	100

Certain loads do not consume their rated power at all times

Bottom-Up Estimation

Aggregating the estimated load for a number of users

$$\hat{E}_{\text{load}} = \sum_{n=1}^{N} \hat{E}_{n,\text{load}}$$

Bottom-Up Estimation

	Quantity	x	Rating (W)	x	Duration of Use/Day	x	Loading Percent	=	Energy Use/Day
	5	x	11W	x	4hrs	x	100/100	=	220 Wh
	1	x	200W	x	24hrs	x	10/100	=	480 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 percent

- Many appliances do not consume constant power
- How should stand-by power be accounted for?

Surveyor bias!

Example 15.5

A mini-grid with a single gen set is to be designed to serve 18 users. A survey approach was used to estimate the load. It is estimated that half of the users will each have appliances whose combined power rating is 89 W, and the other half will each have appliances whose combined power rating is 119 W. The demand factor for each group is estimated to be 0.7. The coincidence factor is estimated to be 0.6. Compute the minimum rated power of the gen set that is needed to supply the anticipated load.

Example 15.5

A mini-grid with a single gen set is to be designed to serve 18 users. A survey approach was used to estimate the load. It is estimated that half of the users will each have appliances whose combined power rating is 89 W, and the other half will each have appliances whose combined power rating is 119 W. The demand factor for each group is estimated to be 0.7. The coincidence factor is estimated to be 0.6. Compute the minimum rated power of the gen set that is needed to supply the anticipated load.

The peak load for the first group of users is:

$$P_{\text{peak}} = DF\sum_{a=1}^{A} P_{a,\max} = 0.7 \times 89 = 62.3\,\text{W}$$

and for the second group of users is 0.7 x 119 = 83.3 W

Example 15.5

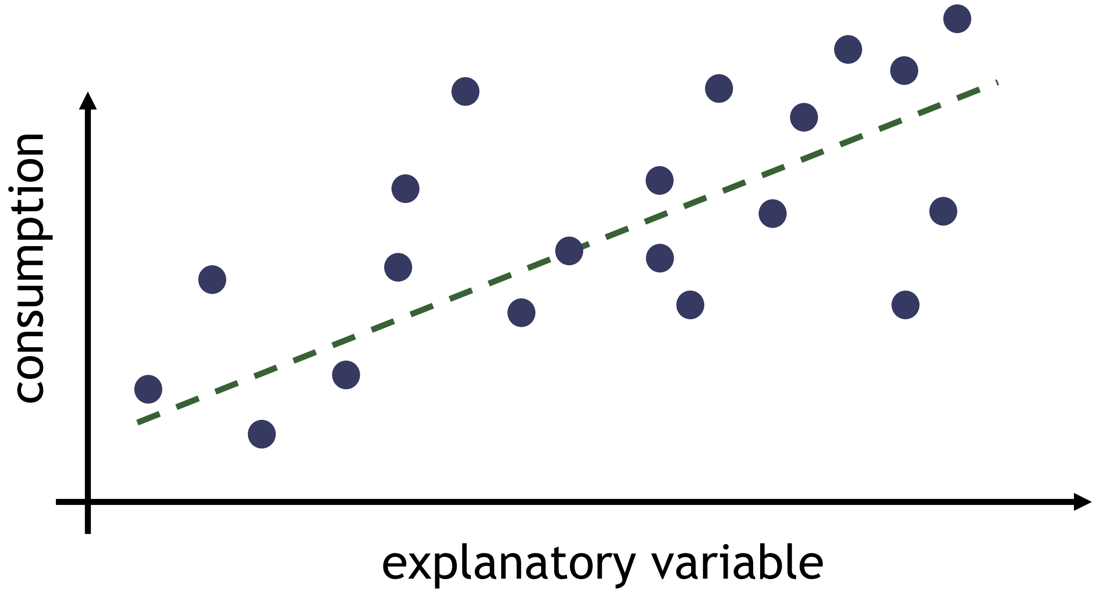
A mini-grid with a single gen set is to be designed to serve 18 users. A survey approach was used to estimate the load. It is estimated that half of the users will each have appliances whose combined power rating is 89 W, and the other half will each have appliances whose combined power rating is 119 W. The demand factor for each group is estimated to be 0.7. The coincidence factor is estimated to be 0.6. Compute the minimum rated power of the gen set that is needed to supply the anticipated load.

The peak load for the combined groups:

$$P_{\text{peak,grp}} = CF \times \sum_{n=1}^{N} P_{\text{peak},n} = 0.6 \times (9 \times 62.3 + 9 \times 83.3) = 786.24\,\text{W}$$

Regression

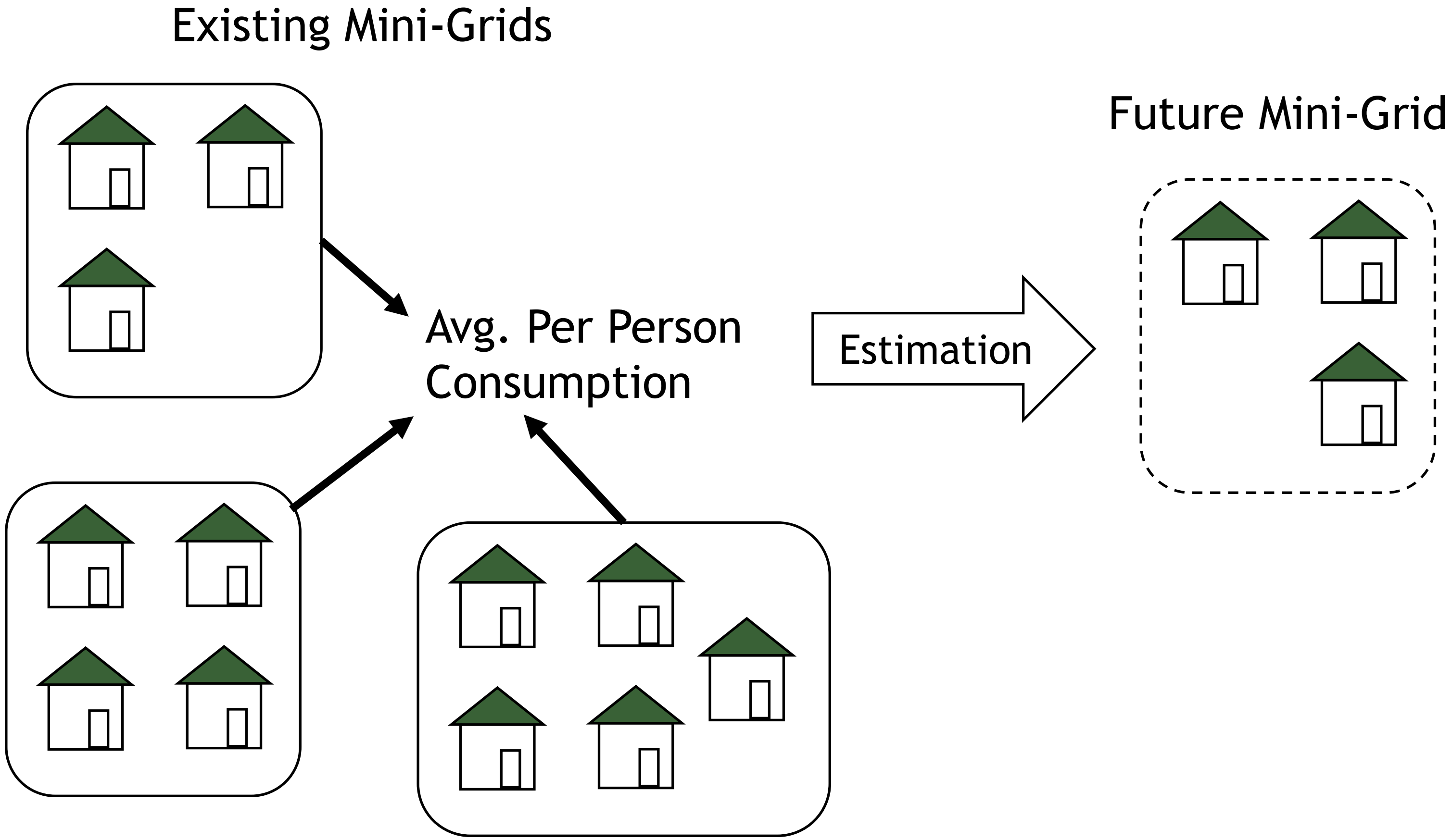
- Use mathematical model based on demographic/census data to estimate usage
- Several explanatory variables proposed
  - number of people living in house
  - income
  - distance to grid
  - presence of a flushing toilet



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

Energy Resource Data Requirements

Conversion Technology	Physical Characteristic	Data Quality	Typical Data Source
PV array	insolation	average per day by month	solar database
Wind Energy Conversion System (WECS)	wind speed	1-2 year time series (preferred) or average by month	direct measurement
Biomass	feedstock type, yield	average yield by month	agricultural database, local observation
Micro hydro (MHP)	head, flow rate	average flow by month or season	direct measurement
Conventional Gen Set	fuel availability	availability by season	local observation

Capacity Factor

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

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

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

Capacity factor is often expressed as a percentage

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

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

Example 15.6

The load of a mini-grid is estimated to be 48 kWh per day. If served by a two-nozzle Pelton turbine, the water resource is such that the capacity factor will be 0.91. If the load is served by a PV array, the capacity factor will be 0.18. Compute the required capacity of the Pelton turbine and the PV array to supply the load.

Example 15.6

The load of a mini-grid is estimated to be 48 kWh per day. If served by a two-nozzle Pelton turbine, the water resource is such that the capacity factor will be 0.91. If the load is served by a PV array, the capacity factor will be 0.18. Compute the required capacity of the Pelton turbine and the PV array to supply the load.

The required capacity of the Pelton turbine is

$$P_{\text{rated,MHP}} = \frac{\hat{E}}{T \times capacity\ factor} = \frac{48.0}{24 \times 0.91} = 2.20\ \text{kW}$$

The required capacity of the PV array is

$$P_{\text{rated,PV}} = \frac{48.0}{24 \times 0.18} = 11.11\ \text{kW}$$

Capacity Factor

Technology	Approx. Capacity Factor	Capacity need to produce 24 kWh/day (kW)
Gen set	0.90-1.00	1.00-1.11
PV	0.15-0.24	4.1-6.67
MHP	0.80-0.95	1.05-1.25
WEC	0.20-0.30	3.33-5.00

Capacity Factors vary substantially for different energy conversion technologies

Lower capacity factors require larger-capacity generation sources to produce the same energy

Solar Resource

- Recall that the 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/m^2/day if t is expressed in hours and G_d are in kW/m^2

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

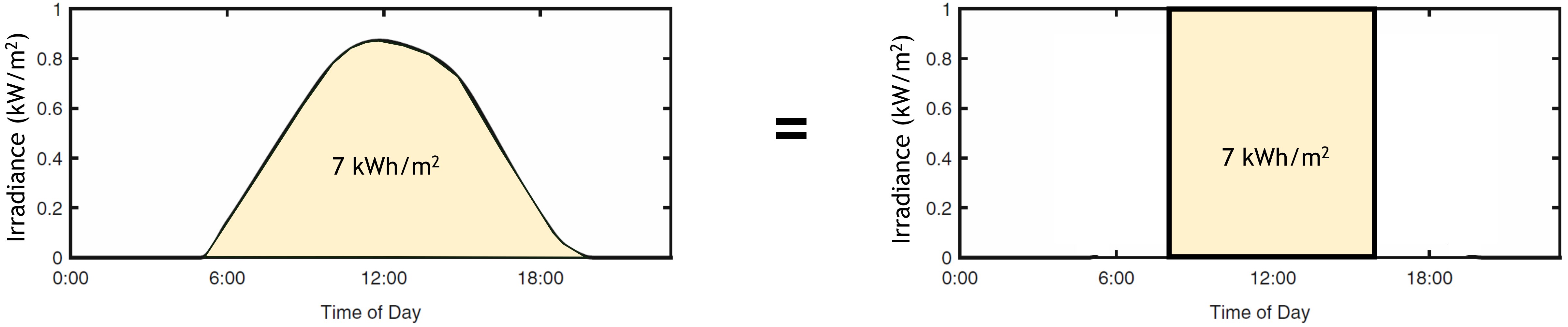
$$\overline{I}_D = \frac{\sum_{d \in \mathcal{D}} I_d}{D}$$

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)

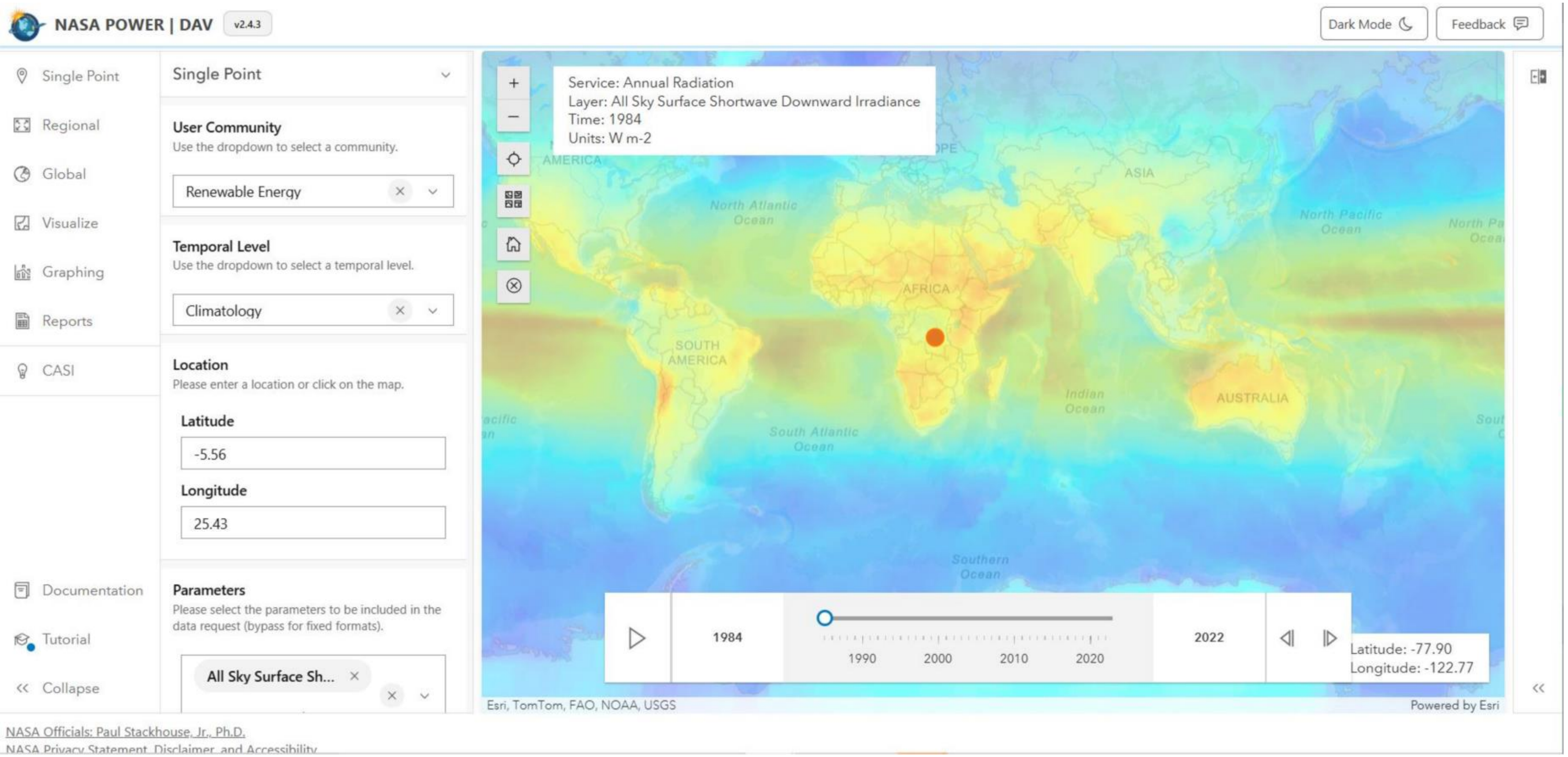


Solar Resource Databases

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

- Example: NASA's Prediction of Worldwide Energy Resources (POWER) Data Access Viewer (DAV)

Solar Resource 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)

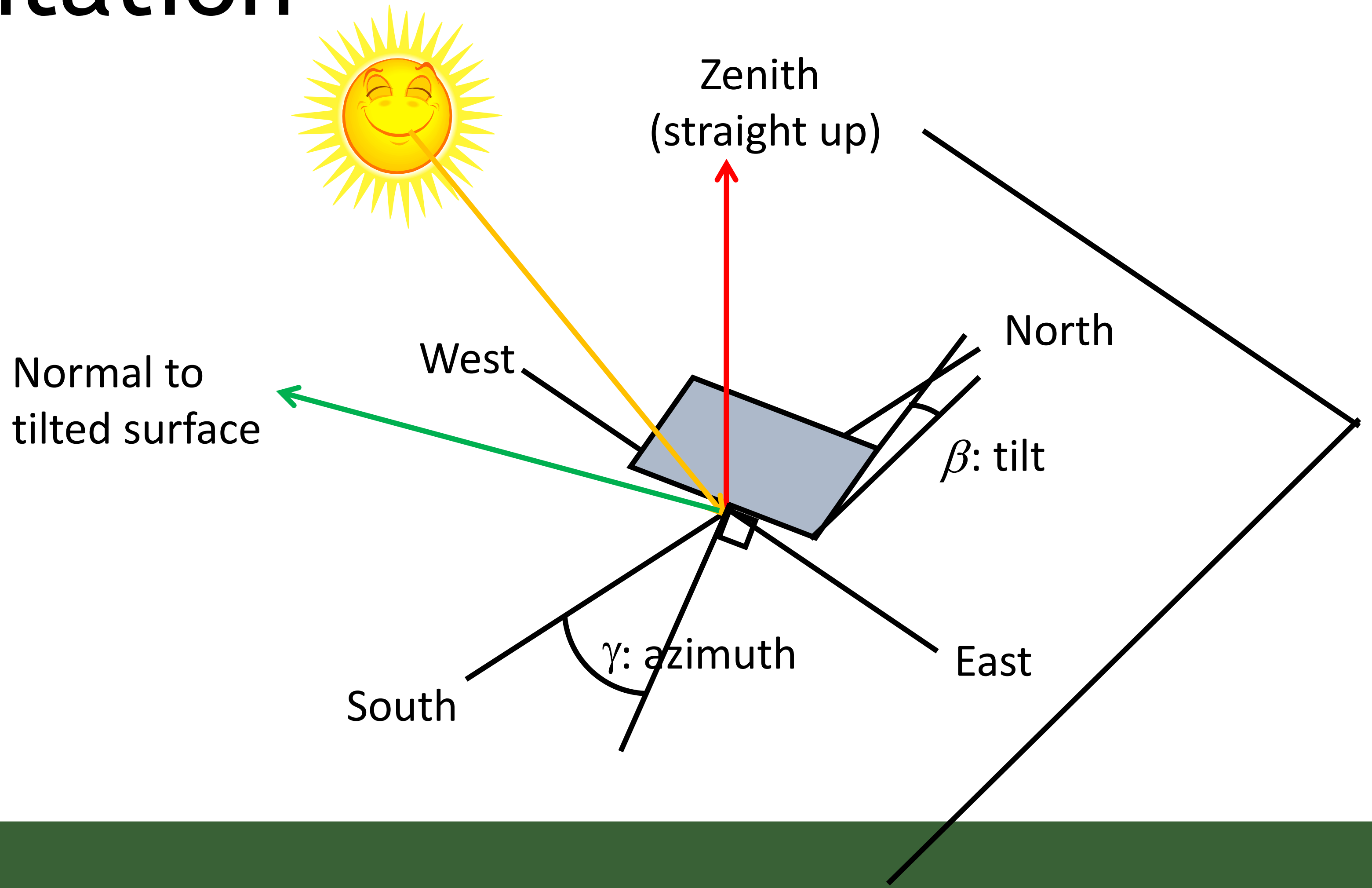
Solar Resource Databases

-BEGIN HEADER-
NASA/POWER Source Native Resolution Climatology in LST
20-year Meteorological and Solar Monthly & Annual Climatologies (January 2001 - December 2020)
Location: Latitude 6.5276 Longitude 30.4534
Elevation from MERRA-2: Average for 0.5 x 0.625 degree lat/lon region = 446.82 meters
The value for missing source data that cannot be computed or is outside of the sources availability range: -999
Parameter(s):
SI_TILTED_AVG_HORIZONTAL SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Horizontal Surface (kW-hr/m^2/day)
SI_TILTED_AVG_LAT_MINUS15 SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Minus 15 Tilt (kW-hr/m^2/day)
SI_TILTED_AVG_LATITUDE SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Tilt (kW-hr/m^2/day)
SI_TILTED_AVG_LAT_PLUS15 SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Latitude Plus 15 Tilt (kW-hr/m^2/day)
SI_TILTED_AVG_VERTICAL SRB V4/CERES SYN1deg Solar Irradiance for Equator Facing Vertical Surface (kW-hr/m^2/day)
SI_TILTED_AVG_OPTIMAL SRB V4/CERES SYN1deg Solar Irradiance Optimal (kW-hr/m^2/day)
SI_TILTED_AVG_OPTIMAL_ANG SRB V4/CERES SYN1deg Solar Irradiance Optimal Angle (Degrees)
SI_TILTED_AVG_OPTIMAL_ANG_ORT SRB V4/CERES SYN1deg Solar Irradiance Tilted Surface Orientation (N/S Orientation)
Message(s):
The requested parameters are retrieved from a pre-computed climatological period (January 2001 - December 2020)
-END HEADER-

Monthly average insolation at various PV array tilts

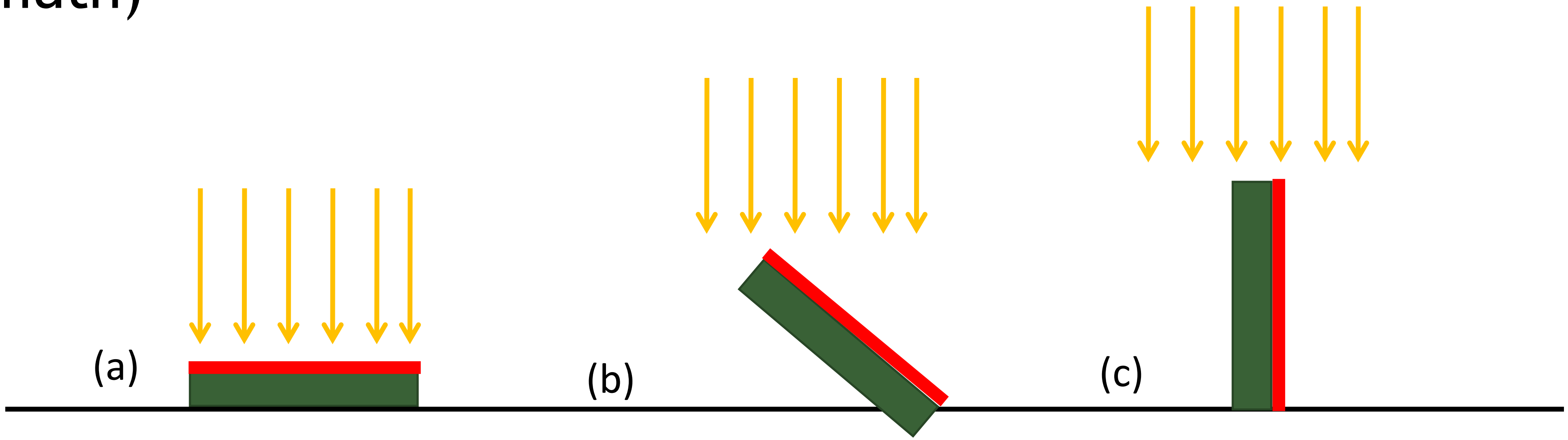
PARAMETER	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
SI_TILTED_AVG_HORIZONTAL	5.75	5.77	5.38	5.14	4.94	4.56	4.32	4.6	5.08	5.12	5.07	5.58	5.14
SI_TILTED_AVG_LAT_MINUS15	5.32	5.48	5.24	5.11	4.97	4.59	4.35	4.58	4.98	4.92	4.76	5.11	5.01
SI_TILTED_AVG_LATITUDE	6.02	5.93	5.43	5.12	4.86	4.49	4.26	4.56	5.1	5.22	5.26	5.87	5.18
SI_TILTED_AVG_LAT_PLUS15	6.4	6.08	5.36	4.89	4.52	4.2	3.99	4.33	4.97	5.27	5.5	6.32	5.11
SI_TILTED_AVG_VERTICAL	3.97	3.2	2.3	1.85	1.77	1.82	1.76	1.78	1.95	2.64	3.28	4.12	2.14
SI_TILTED_AVG_OPTIMAL	6.46	6.08	5.44	5.14	4.97	4.59	4.35	4.6	5.1	5.29	5.52	6.43	5.19
SI_TILTED_AVG_OPTIMAL_ANG	30.5	21	9.5	-0.5	-8.5	-8	-8.5	-3	6	16.5	27	33	9.5
SI_TILTED_AVG_OPTIMAL_ANG_ORT	S	S	S	N	N	N	N	N	S	S	S	S	S

Orientation

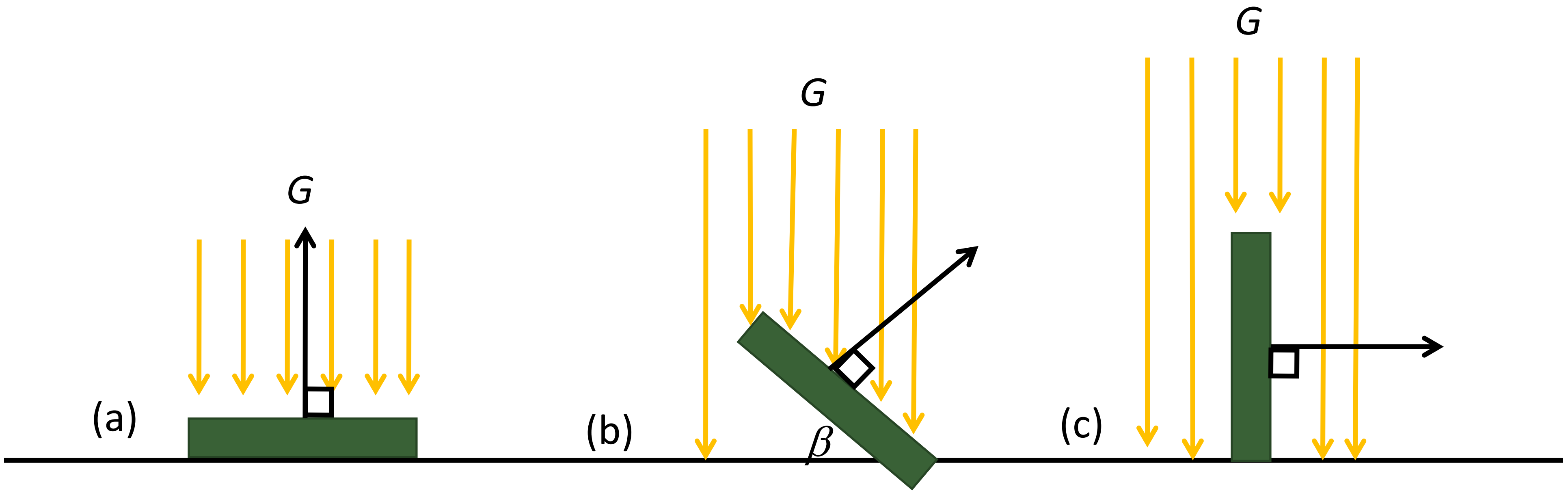


Plane-of-Array Irradiance

Plane-of-array (POA) irradiance: irradiance that is incident to the surface of the PV array, accounting for its orientation (tilt, azimuth)



Plane-of-Array Irradiance



POA irradiance = G POA irradiance = $G\cos(\beta)$ POA irradiance = 0

Plane-of-Array (POA) Irradiance

- Many databases report Global Horizontal Irradiance (GHI), which assumes PV array is horizontal (zero tilt)
- Be sure to use POA irradiance in calculations!
  - algorithms can be used to estimate POA from GHI
- Hereafter we assume irradiance and insolation values are POA

Capacity Factor of a PV Array

- Recall that if temperature effects are ignored, the power produced by a PV array is

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

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

- The estimated energy production for day d is therefore:

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

Capacity Factor of a PV Array

- The estimated total production for a month is therefore:

$$\hat{E}_{\mathrm{PV},D} = \sum_{d\in\mathcal{D}} P^{*}_{\mathrm{STC}} I_d = P^{*}_{\mathrm{STC}} \sum_{d\in\mathcal{D}} I_d = P^{*}_{\mathrm{STC}} \times \overline{I}_{\mathcal{D}} \times D.$$

- And the Capacity Factor is:

$$\textit{capacity factor} = \frac{\hat{E}_{\mathrm{PV},\mathcal{D}}}{24 \times D \times P^{*}_{\mathrm{STC}}} = \frac{P^{*}_{\mathrm{STC}} \overline{I}_{\mathcal{D}} D}{24 \times D \times P^{*}_{\mathrm{STC}}} = \frac{\overline{I}_{\mathcal{D}}}{24}$$

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

Capacity Factor of a PV Array

- This result is useful for back-of-the-envelope calculations and preliminary design
- We must remember that PV arrays are affected by temperature and there are other losses that should be accounted for during the design stage
- Typical insolation for SSA ranges from 4 to 7 kWh/m^2/day, depending on the location and season
- Keep in mind that the insolation must correspond to the plane that the PV array will be installed

Exercise

The average insolation on a PV module rated at 350 W for the month of July is 4.7 kWh/m^2/day. What is the average energy produced by the module each day? What is the corresponding capacity factor?

Exercise

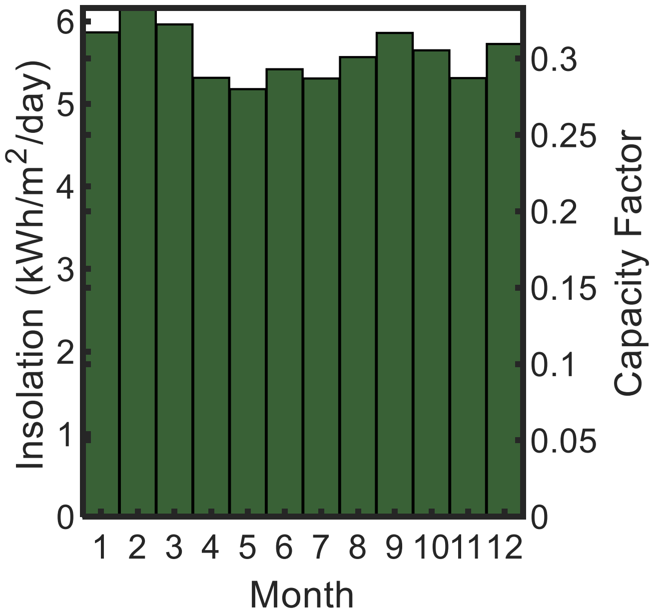
The average insolation on a PV module rated at 350 W for the month of July is 4.7 kWh/m^2/day. What is the average energy produced by the module each day? What is the corresponding capacity factor?

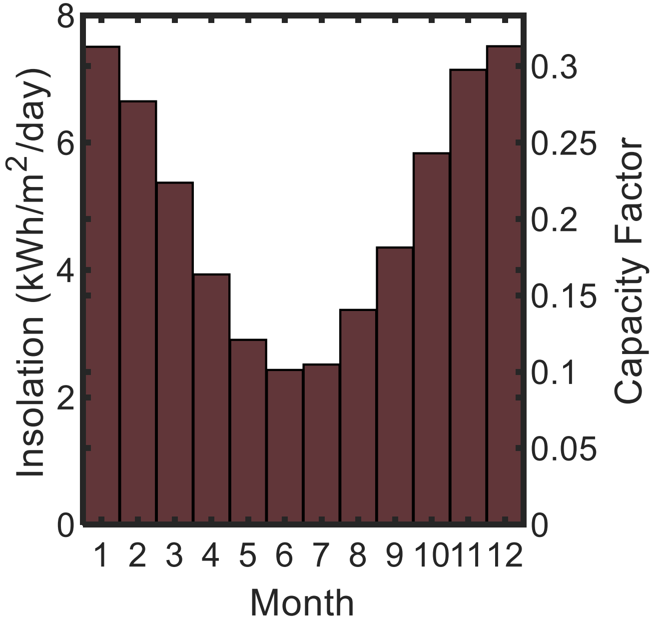
$$\bar{E}_{PV} = 350 \times 4.7 = 1645 \text{ Wh}$$

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

Capacity Factor is Influenced by

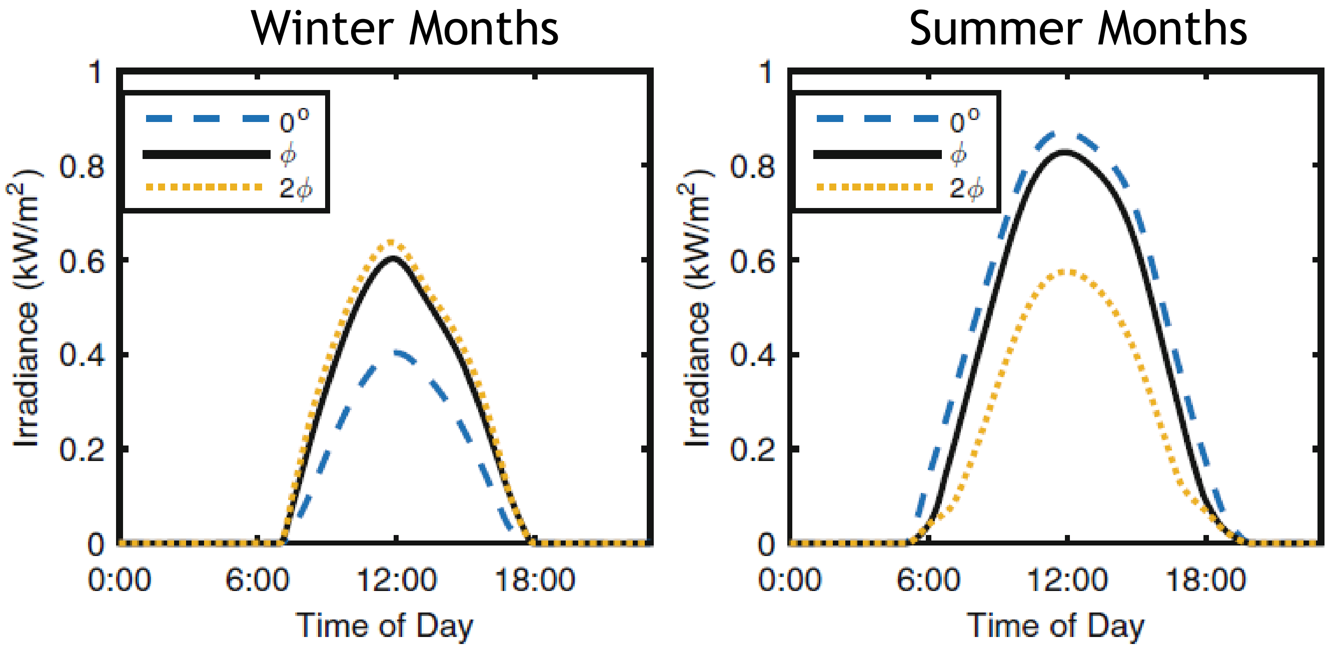
- Season (day of year)
- Location (lat. and long.)
- Weather conditions
- Orientation of array





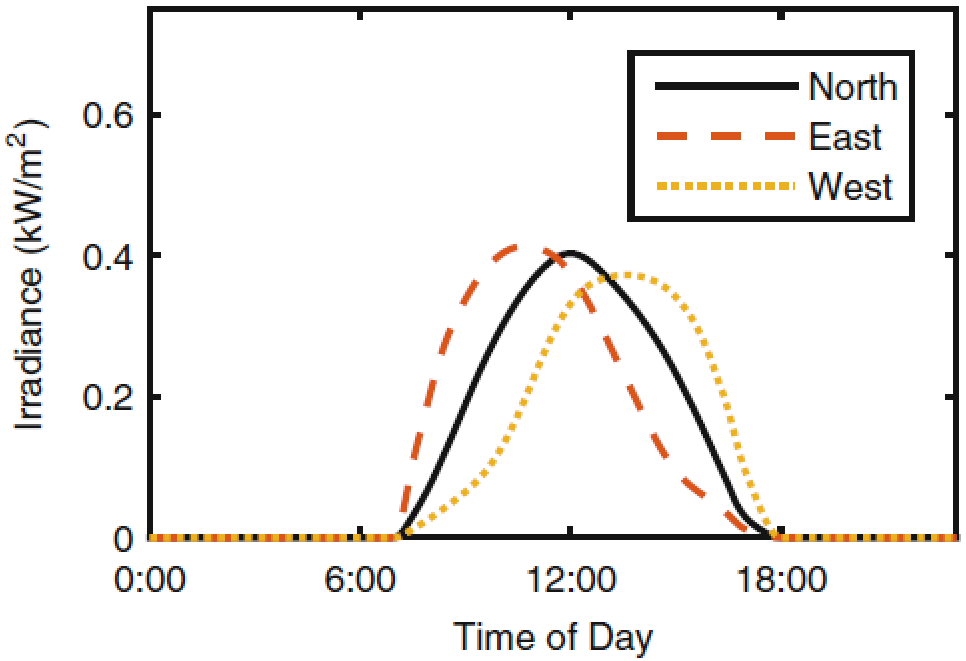
Insolation and capacity factor for
a horizontal arrays near the equator and 34° S

Effects of Tilt



Effects of Azimuth

Azimuth is the skewness from north or south



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*)

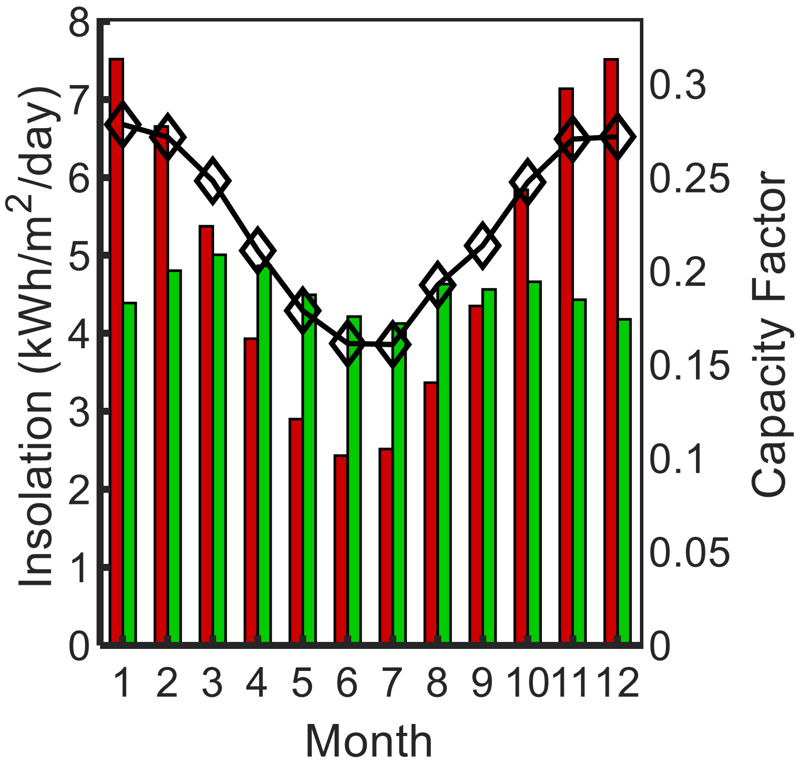
Singapore (1 °N)

(*courtesy: H. Louie*)

Effects of Tilt (location 34 °S)

Horizontal (0° tilt)
Latitude (34° tilt)
Twice latitude (68° tilt)

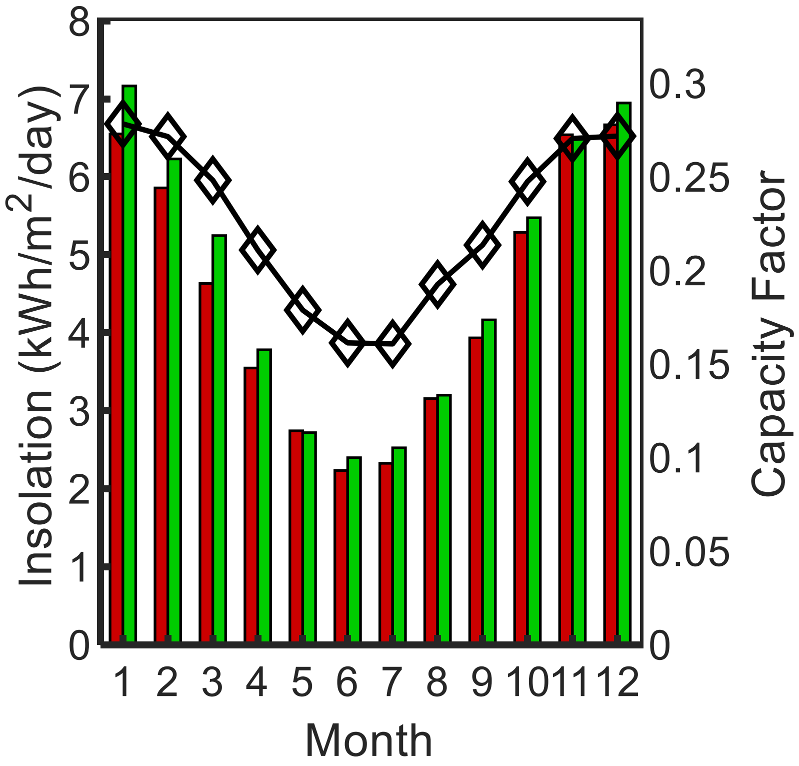
Tilting at latitude offers highest average capacity factor



Effects of Azimuth (location 34 °S)

West (34° tilt)
North (34° tilt)
East (34° tilt)

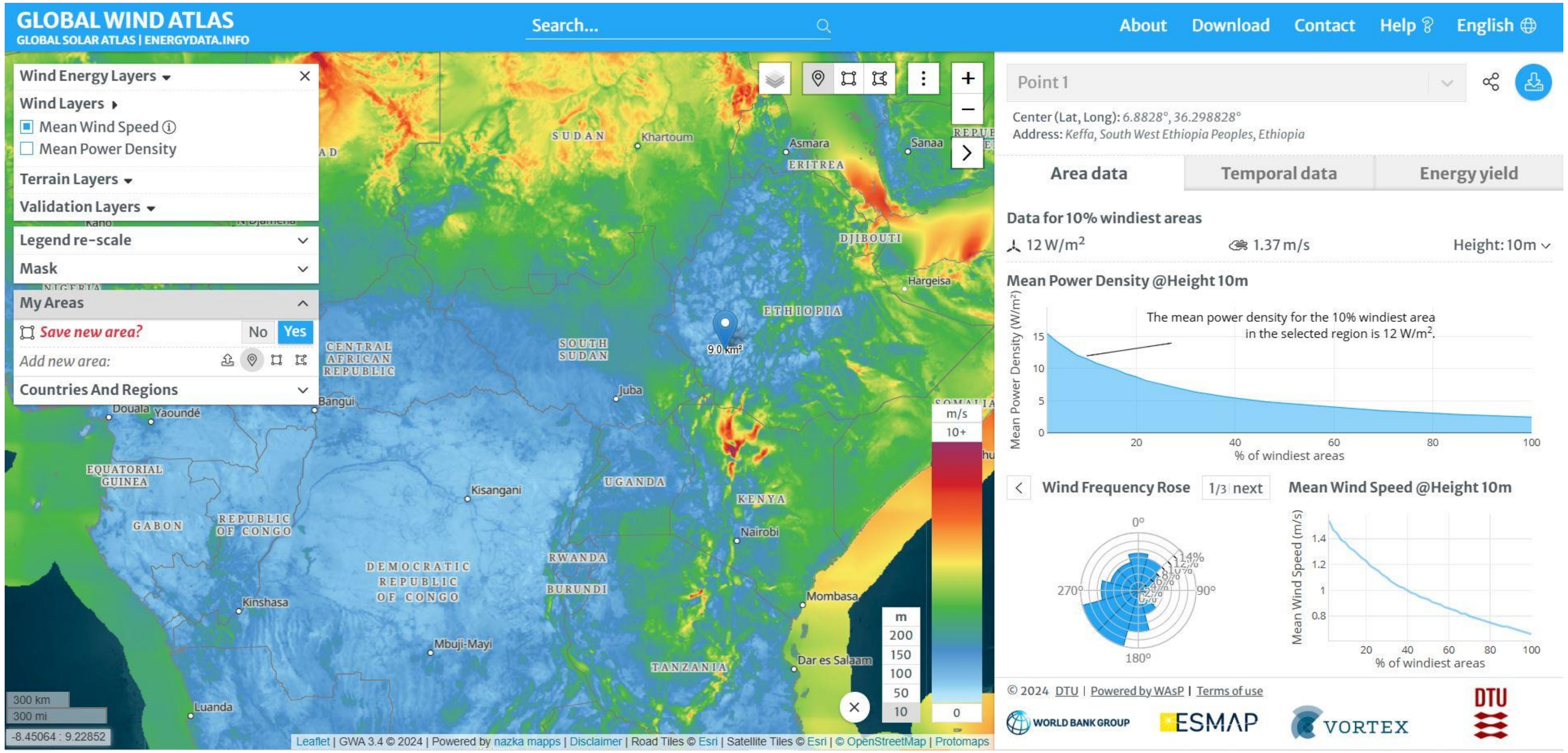
North-facing offers highest capacity factor



Wind Resource

- Energy produced by WECS depends on its power curve and wind speed at hub height
- Wind speed can vary significantly over short distances, making assessing its suitably difficult
    - online databases can be used for general prospecting
    - local measurement needed

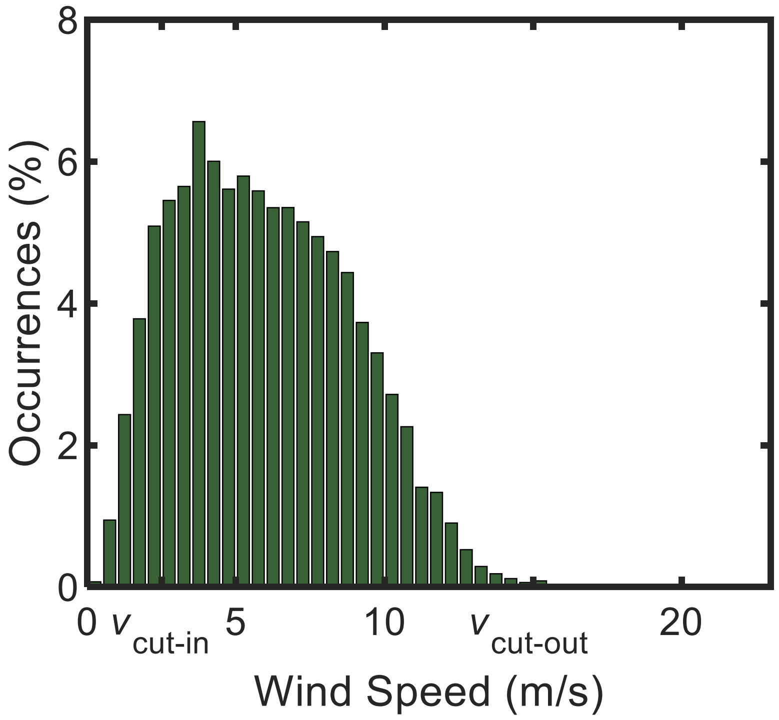
Wind Resource



Global Wind Atlas version 3.3, a free, web-based application
developed, owned and operated by the Technical University of Denmark (DTU). The Global
Wind Atlas version 3.3 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using
funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information:
https://globalwindatlas.info. It is licensed under CC BY 4.0

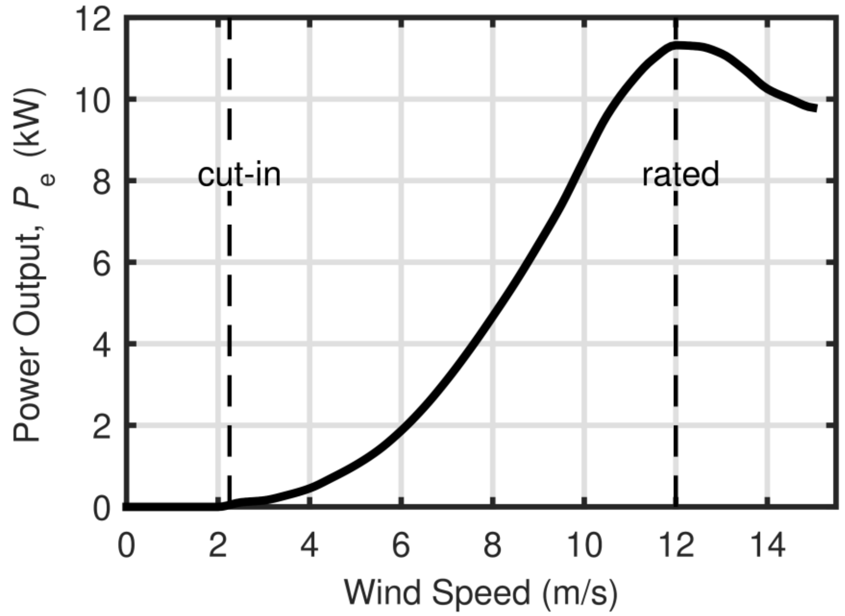
Wind Resource

- Local wind speed samples can be measured using an anemometer mounted atop a tall pole or tower
- Recommended measure at least one year of data to capture seasonal variations
- Create histogram of wind speed



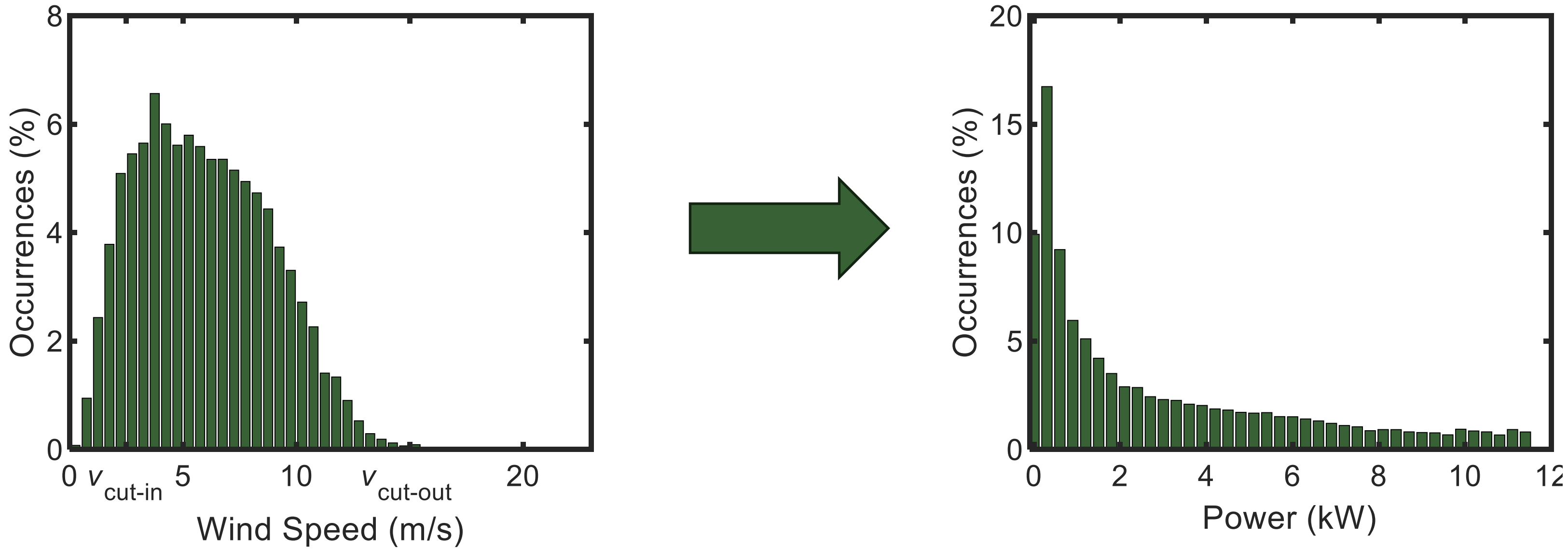
Capacity Factor

Capacity factor depends on wind resource and the power curve of the chosen WECS (see Chap. 8)



Capacity Factor

Power curve transforms the histogram of wind speed to histogram of power



Capacity Factor

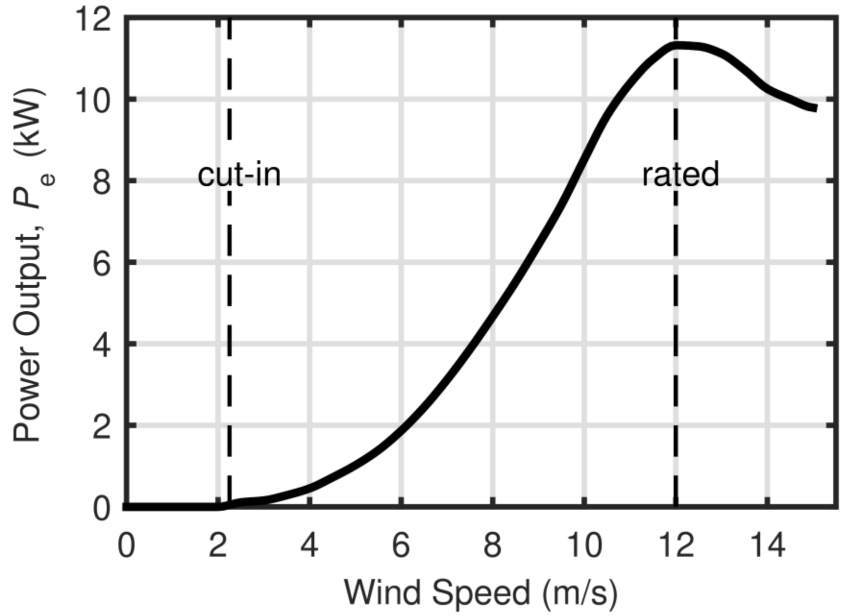
- Capacity factor depends on wind resource and the power curve of the chosen WECS (see Chap. 8)
- Power at time t from WECS is a function $g()$ of wind speed $v(t)$

$$P_{\text{WECS}}(t) = g(v(t))$$

- Energy production per month

$$\hat{E}_{\text{WECS},D} = 24 \times D \times \frac{\sum_{t \in D} P_{\text{WECS}}(t)}{s}$$

number of samples per month



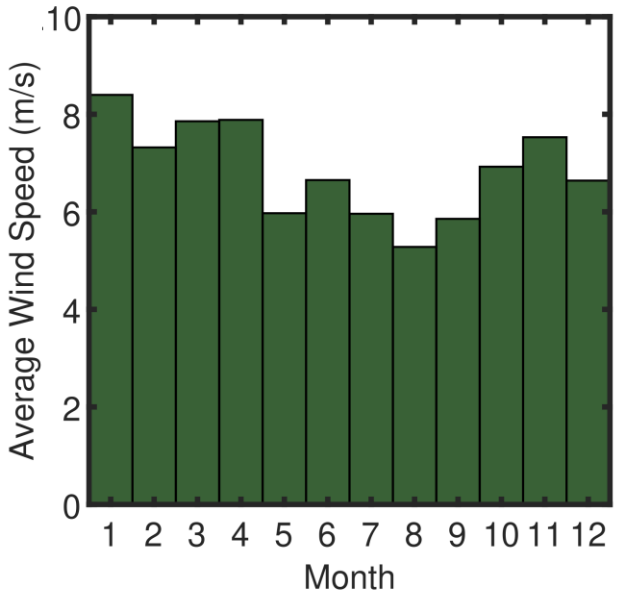
Capacity Factor

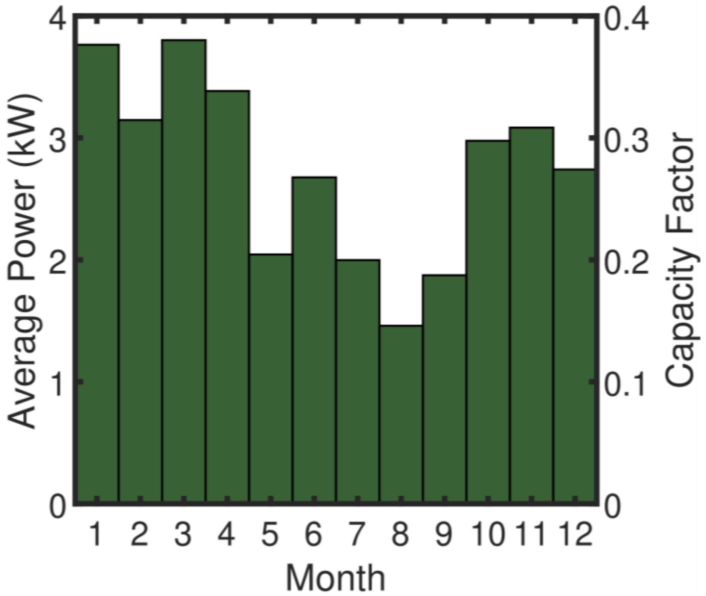
Capacity factor

$$capacity\ factor = \frac{\hat{E}_{\text{WECS},D}}{24 \times D \times P_{\text{WECS,rated}}}$$

rated power of WECS

Capacity Factor by Month





Notice that the capacity factor is not proportional to the average wind speed

Wind Speed Model

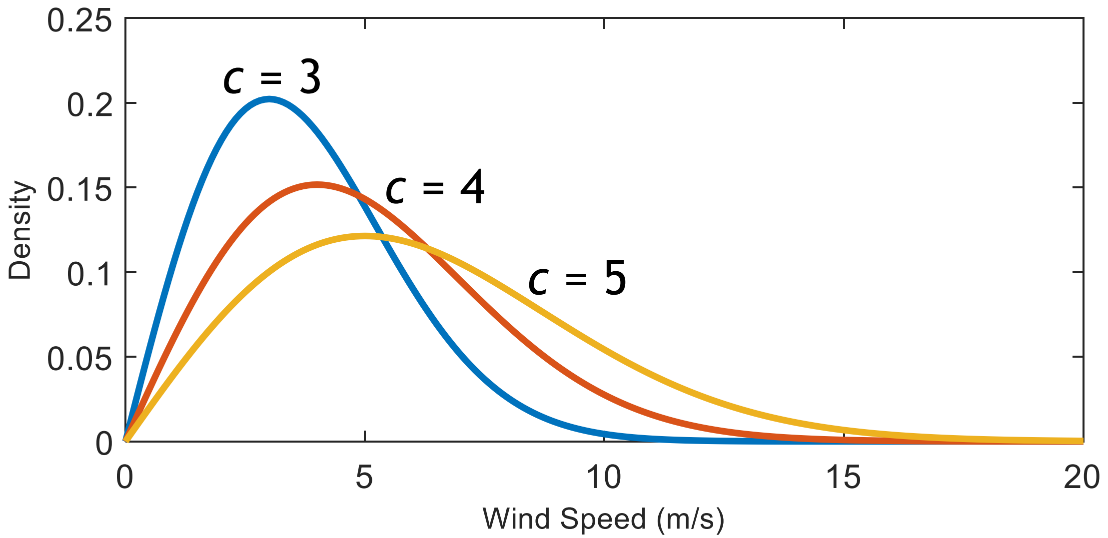
- If measured wind speed data is not available or is incomplete, use a probabilistic model to estimate wind resource
- Assume wind speed is a random variable $\tilde{v}$ belonging to a certain distribution with a known probability density function
- Parametric probability density functions used to model wind speed
  - Rayleigh
  - Weibull

Wind Speed Model

- Rayleigh distribution with wind speed as a random variable $\tilde{v}$:

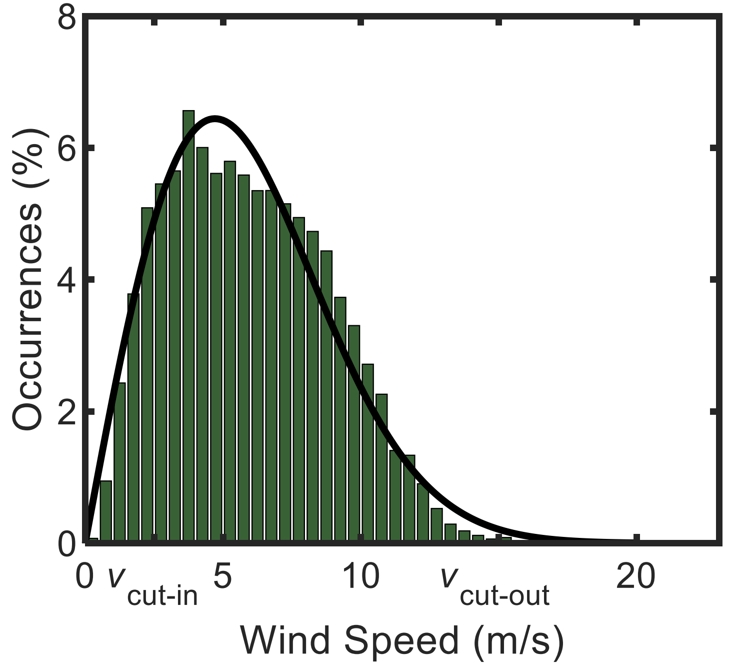
$$f(\tilde{v}) = \begin{cases} \dfrac{\tilde{v}}{c^2} e^{(-\tilde{v}^2/2c^2)} & : \tilde{v} > 0 \\ 0 & : \tilde{v} \le 0 \end{cases}$$

- Parameter c found from: $c = \dfrac{\bar{v}\sqrt{2}}{\sqrt{\pi}}$



Wind Speed Model

Model can be used to estimate capacity factor or compute other values of interest such as portion of time below cut-in or above cut-out



Example 15.9

The average wind speed at the location for a potential mini-grid is 4 m/s. A WECS whose cut-in speed is 2 m/s is considered for the location. Estimate the percentage of the time the wind will be below the cut-in wind speed.

Example 15.9

The average wind speed at the location for a potential mini-grid is 4 m/s. A WECS whose cut-in speed is 2 m/s is considered for the location. Estimate the percentage of the time the wind will be below the cut-in wind speed.

Solving for the parameter *c*

$$c = \frac{\bar{v}\sqrt{2}}{\sqrt{\pi}} = \frac{4\sqrt{2}}{\sqrt{\pi}} = 3.19$$

Example 15.9

The average wind speed at the location for a potential mini-grid is 4 m/s. A WECS whose cut-in speed is 2 m/s is considered for the location. Estimate the percentage of the time the wind will be below the cut-in wind speed.

The portion of the time that the wind speed is below the cut-in can be found from the cumulative distribution function (cdf) of the Rayleigh distribution $F(\tilde{v})$

$$F(\tilde{v}) = \begin{cases} \int f(\tilde{v})d\tilde{v} = 1 - e^{-\tilde{v}^2/2c^2} & : \tilde{v} > 0 \\ 0 & : \tilde{v} \leq 0 \end{cases}$$

Example 15.9

The average wind speed at the location for a potential mini-grid is 4 m/s. A WECS whose cut-in speed is 2 m/s is considered for the location. Estimate the percentage of the time the wind will be below the cut-in wind speed.

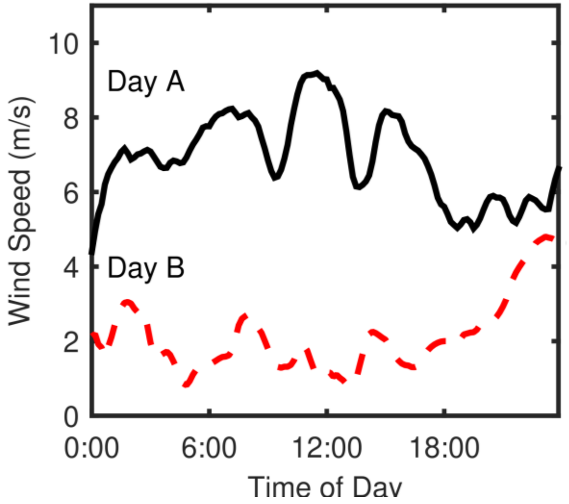
Evaluating the cdf between zero and the cut-in wind speed of 2 m/s yields

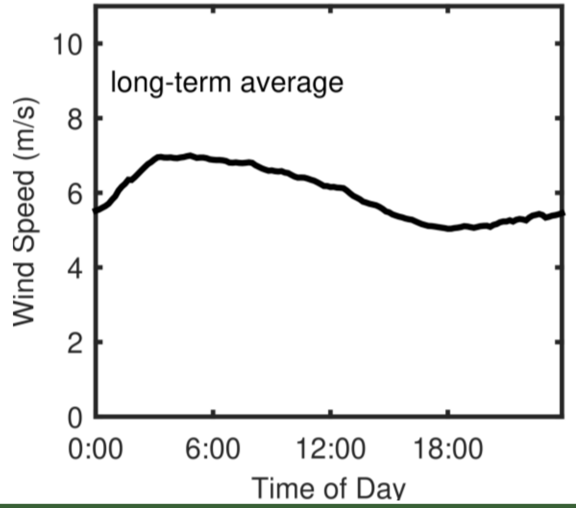
$$F(\tilde{v}) = F(\tilde{v}) = \left(1 - e^{-2^2/2\times 3.19^2}\right) - 0 = 0.178$$

The WECS will not produce power 17.8% of the hours due to the wind speed being below cut-in

Considerations

- Wind speed can vary widely throughout the day
- Day-to-day variation can also be appreciable and can differ from the long-term average





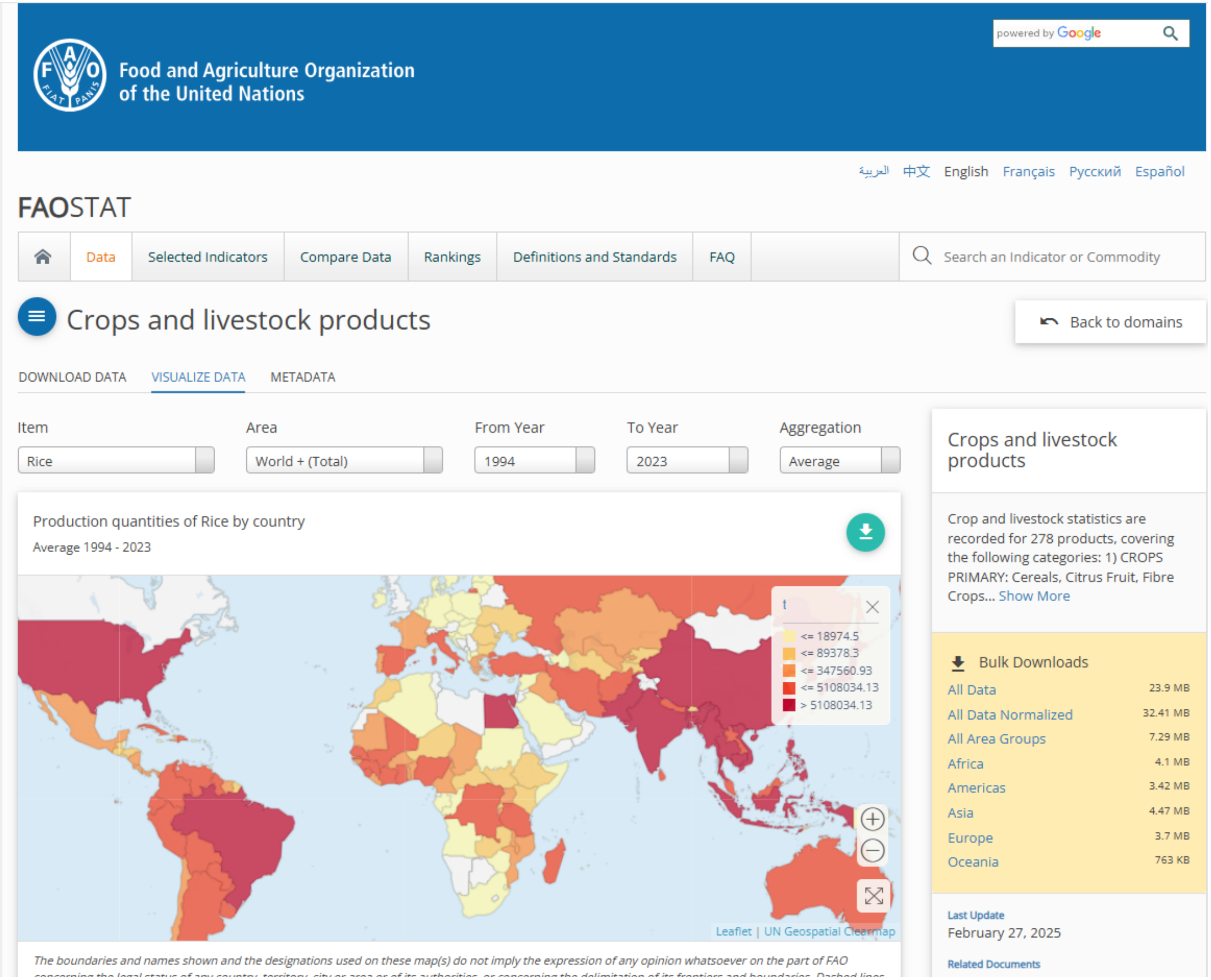
Biomass Resource

Feedstock characteristics

- What type is available?
- Where is it located?
- What are the costs to procure, transport, store and process?

Biomass Resource

United Nations Food and Agriculture Organization database contains information about crop type and yield



www.fao.org/faostat/en

Crop Residue Resource

- Crop residue:

mass of crops

$$crop\ \ residues = crop\ \ yield \times r$$

residue-to-crop ratio, which can exceed 1

- Crop residue available for biomass processing

$$available\ \ crop\ \ residues = \left(crop\ \ residues \times \eta_{\text{coll}}\right) - alternative\ \ residue\ \ uses$$

collection efficiency factor

Crop Residue Resource

- Input energy to gasifier

$$\hat{E}_{\text{in}} = available\ \ crop\ \ residues \times specific\ \ energy$$

Energy (MJ) per unit mass

- Energy production from syngas-fueled generator

$$\hat{E}_{\text{B}} = \hat{E}_{\text{in}} \times \eta_{\text{reactor}} \times \eta_{\text{genset}}$$

- Capacity Factor

$$capacity\ factor = \frac{\hat{E}_{\text{B}} \times \dfrac{1}{3.6}}{24 \times D \times P_{\text{genset,rated}}}$$

D days considered

Biomass Resource Considerations

- Seasonal availability of crops is important, so availability should be computed by month or season
- Droughts may affect availability
- Diesel availability must also be assessed for biomass used in dual-fuel gen sets

Hydro Resource

Assessment of hydro resource:

- flow rate: available flow of water each month or season
- elevation head: vertical distance between turbine location and water intake

Flow Rate Measurements

Flow rate measurement techniques

- divert all or portion of stream into a container with known volume; calculate the time needed to fill
- notched weir: install a weir across the stream, measure the height of water flowing over the weir and use a weir table to estimate velocity
- salt dilution: pour salt upstream and measure the conductivity at a fixed distance downstream; measure the time it takes to reach
- float: measure the time it takes for a floating object to travel a known distance; average velocity is 0.6-0.8 slower than surface velocity
- others

Elevation Head Measurements

Elevation head measurement techniques

- portable altimeter
- topographic station
- hose with pressure gauge

Hydro Resource

- MHP uses a portion of the total flow
- Maximum MHP flow:

$$Q_{\text{MHP,max}} = total\ \ flow\ \ rate - minimum\ \ stream\ \ flow\ \ rate$$

Determined by ecological, agricultural, human use, etc. constraints

Capacity Factor

- Power produced by MHP for a given flow rate and head discussed in Chap. 9
- Power in water:

$$P_{\text{wa}} = \rho_{\text{wa}} \times g \times H \times Q$$

lower flow rate proportionally reduces power

- Estimate energy production over *D* days

$$\hat{E}_{\text{MHP}} = 24 \times D \times P_{\text{MHP}}(\bar{Q})$$

average flow rate

Capacity Factor

- Capacity factor:

$$capacity\ factor = \frac{\hat{E}_{\text{MHP}}}{24 \times D \times P_{\text{MHP,rated}}} = \frac{P_{\text{MHP}}(\bar{Q})}{P_{\text{MHP,rated}}}$$

- If efficiency is assumed to be constant regardless of flow rate

$$capacity\ factor = \min\left\{\frac{\bar{Q}}{Q_{\text{rated}}}, 1.0\right\}$$

Example 15.10

A small mini-grid is being designed for a community. The elevation head was measured to be 29 m, and the flow rate was measured four times during the year. The average measured total flow rates are shown in the Table. At least 15 liter/s of flow must be maintained in the stream for other purposes. Estimate the capacity factor of Pelton turbines designed for a flow of 185 l/s and 8 l/s for each month.

	Jan.	Mar.	Jul.	Sept.	Avg.
Total Flow (liter/s)	30	200	20	28	69.5

Example 15.10

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Total Flow (liter/s)	30	200	20	28	69.5
Max MHP Flow (liter/s)	15	185	5	13	54.5
Capacity Factor (185 liter/s turbine)	0.081	1.0	0.027	0.07	0.295

Turbine is underutilized much of the year

Example 15.10

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Max MHP Flow (liter/s)	15	185	5	13	54.5
Capacity Factor (185 liter/s turbine)	0.081	1.0	0.027	0.07	0.295
Capacity Factor (8 liter/s turbine)	1.0	1.0	0.625	1.0	0.906

Smaller turbine has higher capacity factor, but would produce less energy overall

Conventional Gen Set Resource

- Availability of petrol, diesel, and/or natural gas should be assessed
- Considerations:
  - transportation of fuel, including during rainy season
  - availability of on-site storage
  - disruptions due to fuel shortages
  - price volatility

Summary

- Off-grid system design inputs: characterization of load and energy resource
- Load characteristics of interest: average load, load profile, peak, variation, growth
- Load estimation techniques: bottom-up, survey, regression, data-driven

Summary

- Energy resource characterization requirements vary based on generation source
  - solar: insolation; online databases can be used
  - wind: wind speed; local measurements preferred
  - biomass: crop type and yield; national statistics
  - hydro: flow rate and elevation head; local measurements needed
  - gen set: fuel availability and cost; local or national statistics
- Capacity factor is useful in understanding the utilization of a generation source for a given energy resource