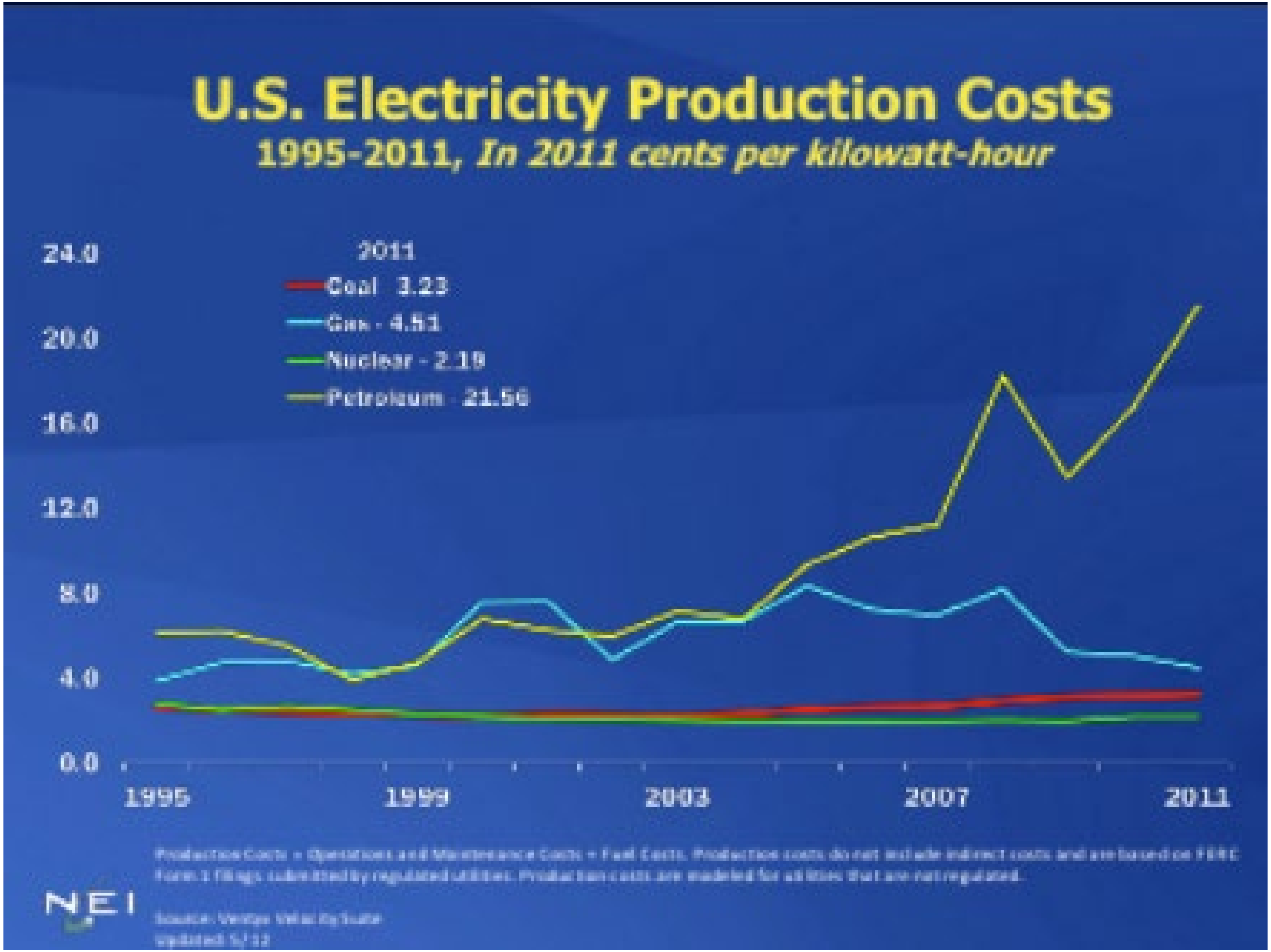
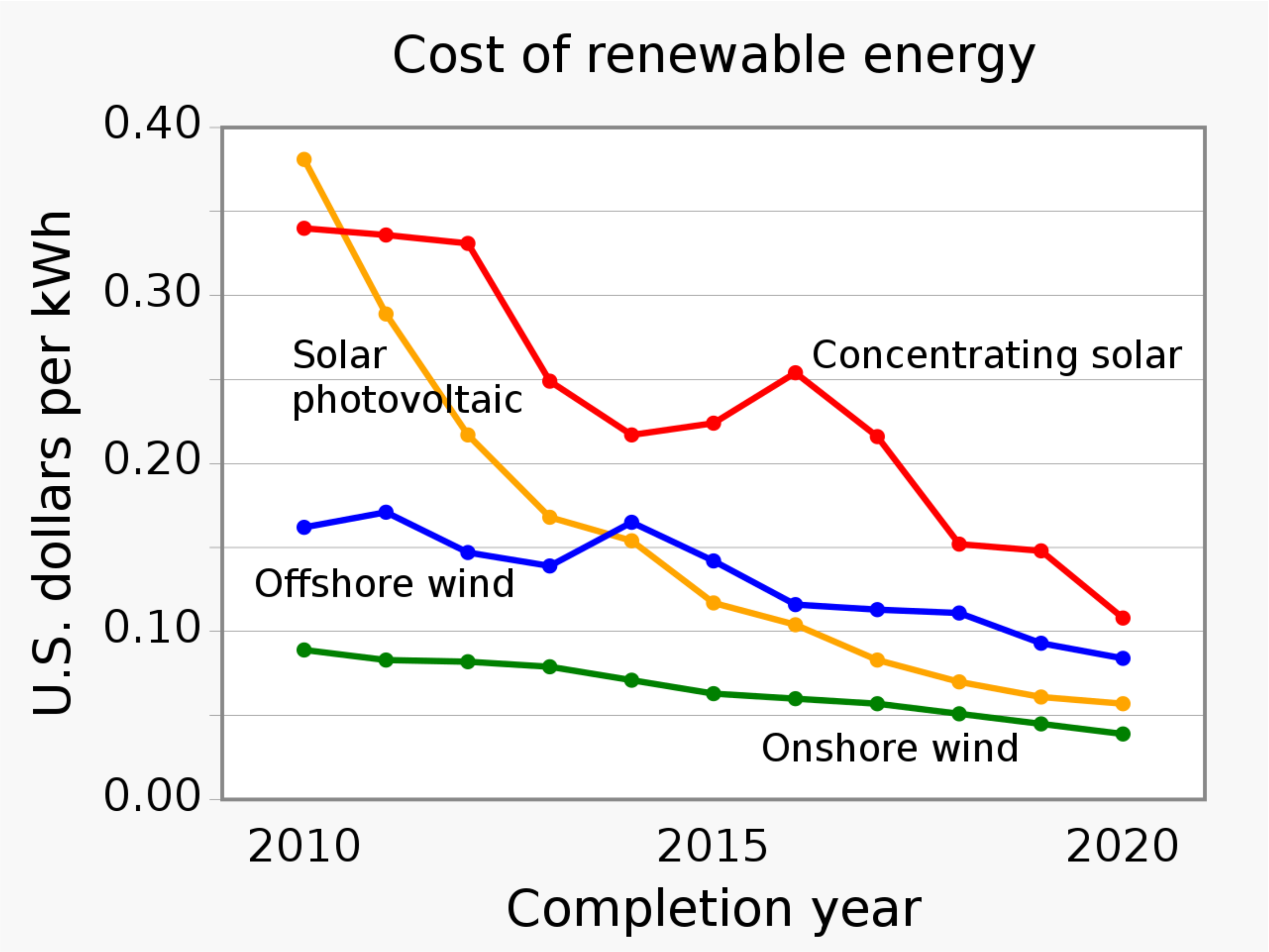
Simple Solar Power Model
Lecture 13

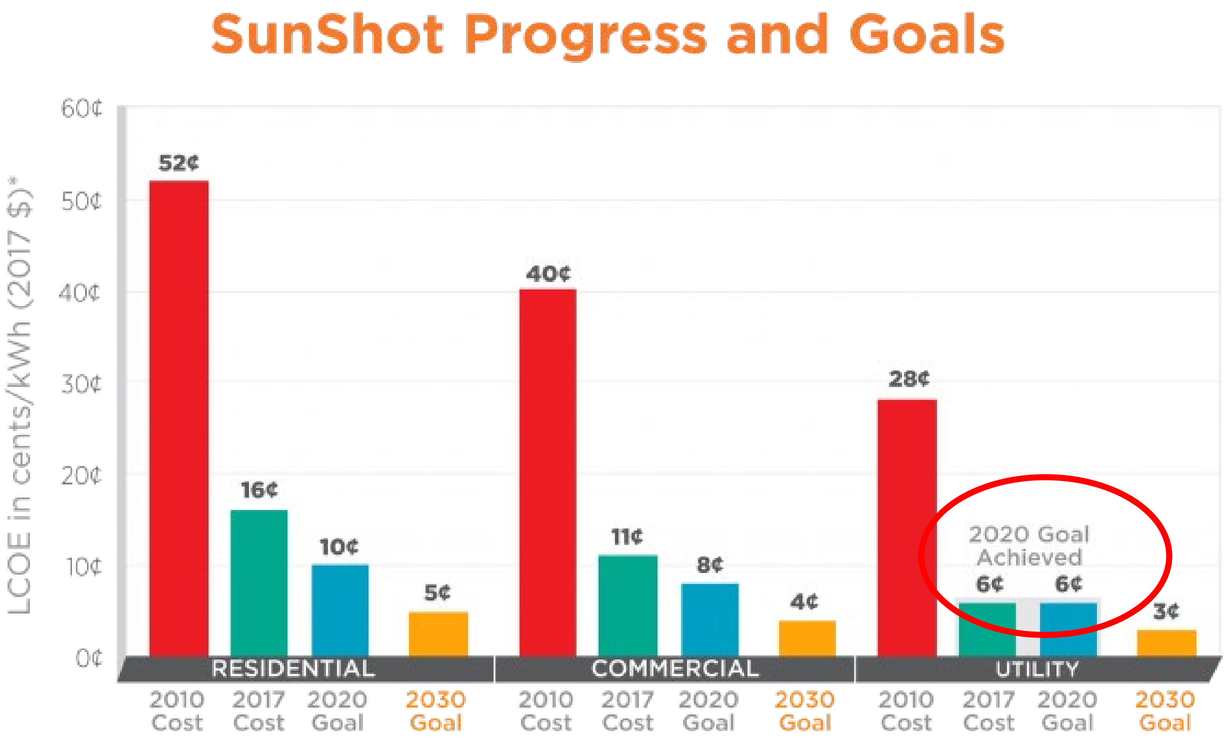
BSEN 5250/6250

Deterministic Modeling for Biosystems


U.S. Electricity Production Costs
1995-2011, In 2011 cents per kilowatt-hour
2011
Coal 3.23
Gas - 4.51
Nuclear - 2.19
Petroleum - 21.56
24.0
20.0
16.0
12.0
8.0
4.0
0.0
1995
1999
2003
2007
2011
Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated.
NEI
Source: Ventyx Velocity Suite
Updated 5/12


Cost of renewable energy
U.S. dollars per kWh
0.40
0.30
0.20
0.10
0.00
Solar
photovoltaic
Concentrating solar
Offshore wind
Onshore wind
2010
2015
2020
Completion year

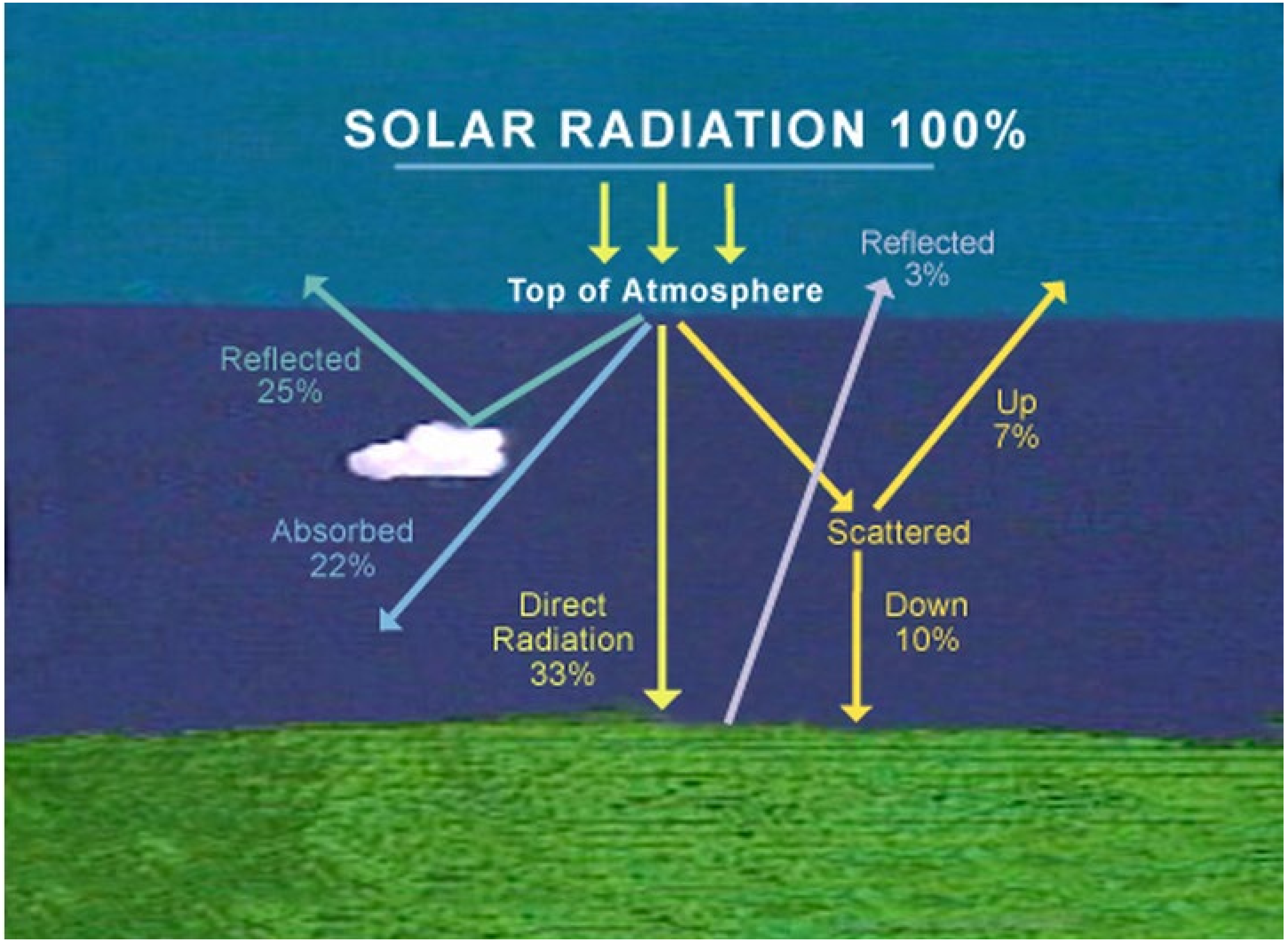
Levelized Cost of Solar Power



*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010-17.

By 2023, China will have the capacity to deploy solar power nationwide at the same price as coal, and currently has that ability in three-quarters of the country, according to a joint study from Harvard, Tsinghua, Nankai and Renmin universities.

Energy From the Sun

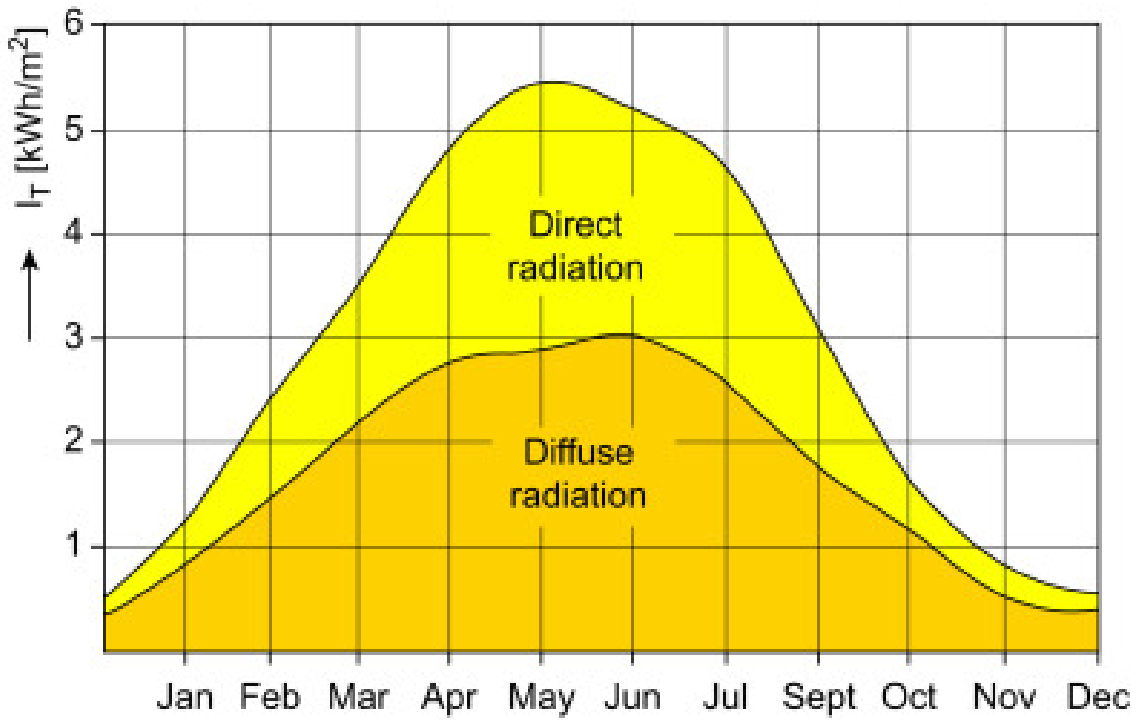


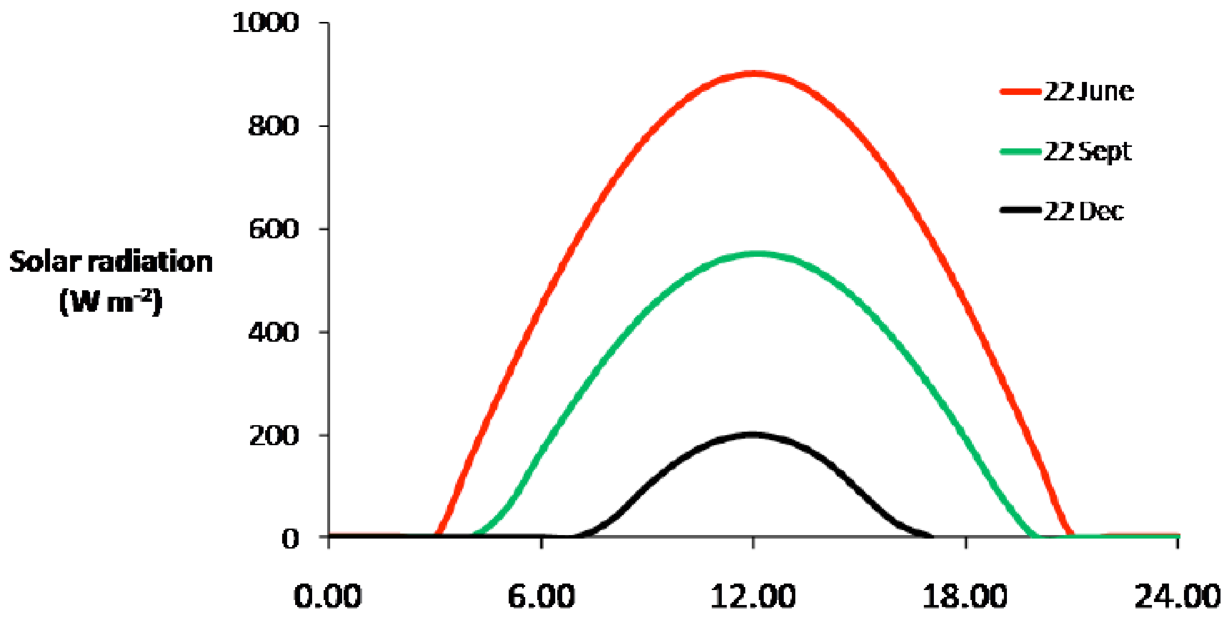
173,000 trillion watts of solar radiation hits earth continuously

Sun provides more energy to earth in 1 hour than we consume in 1 year globally.

A 50 m^2 area of earth receives approximately 288 KW of energy each day, or 10 times daily household use.

Changes in Solar Radiation

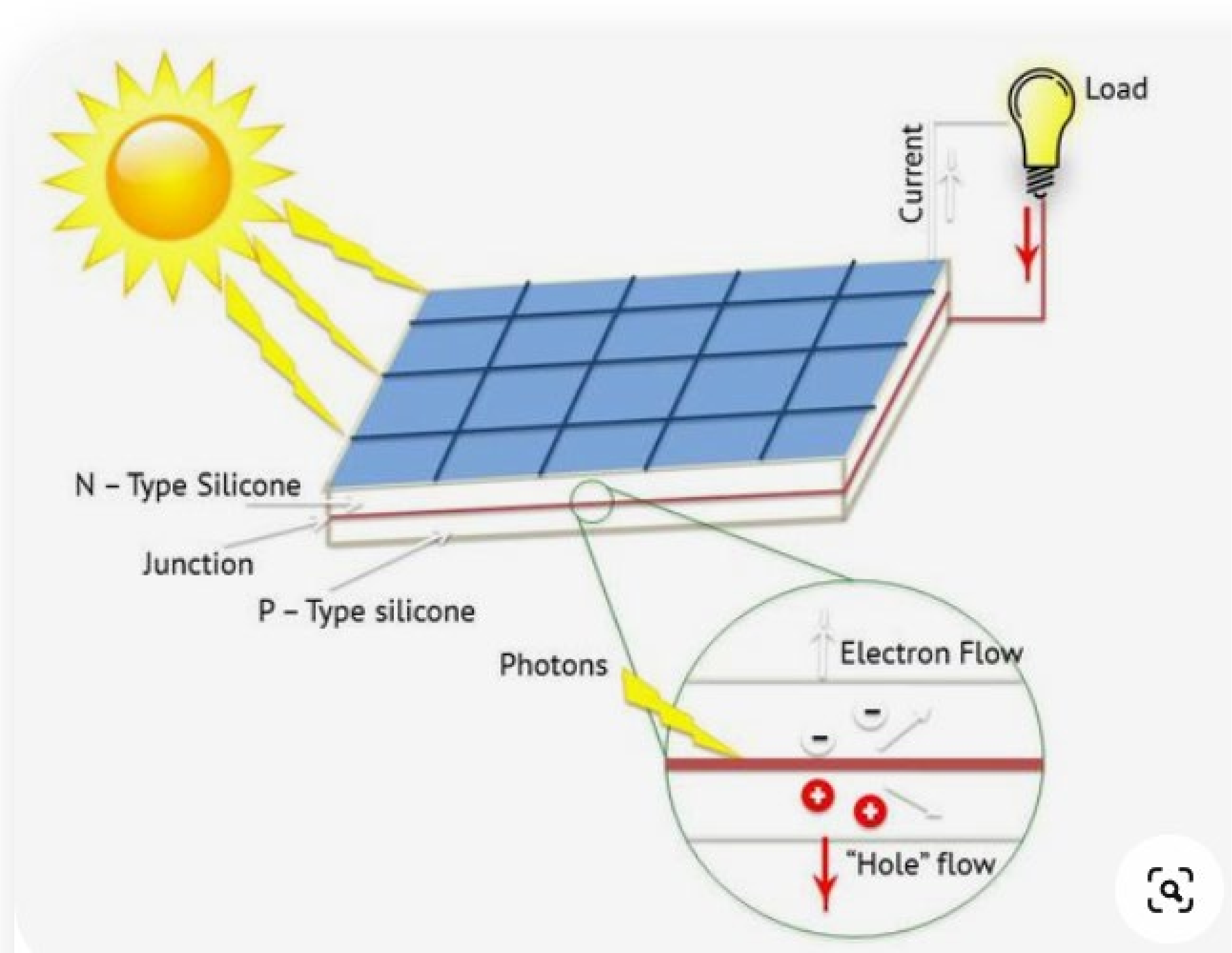




Annual Trend

Daily Trend

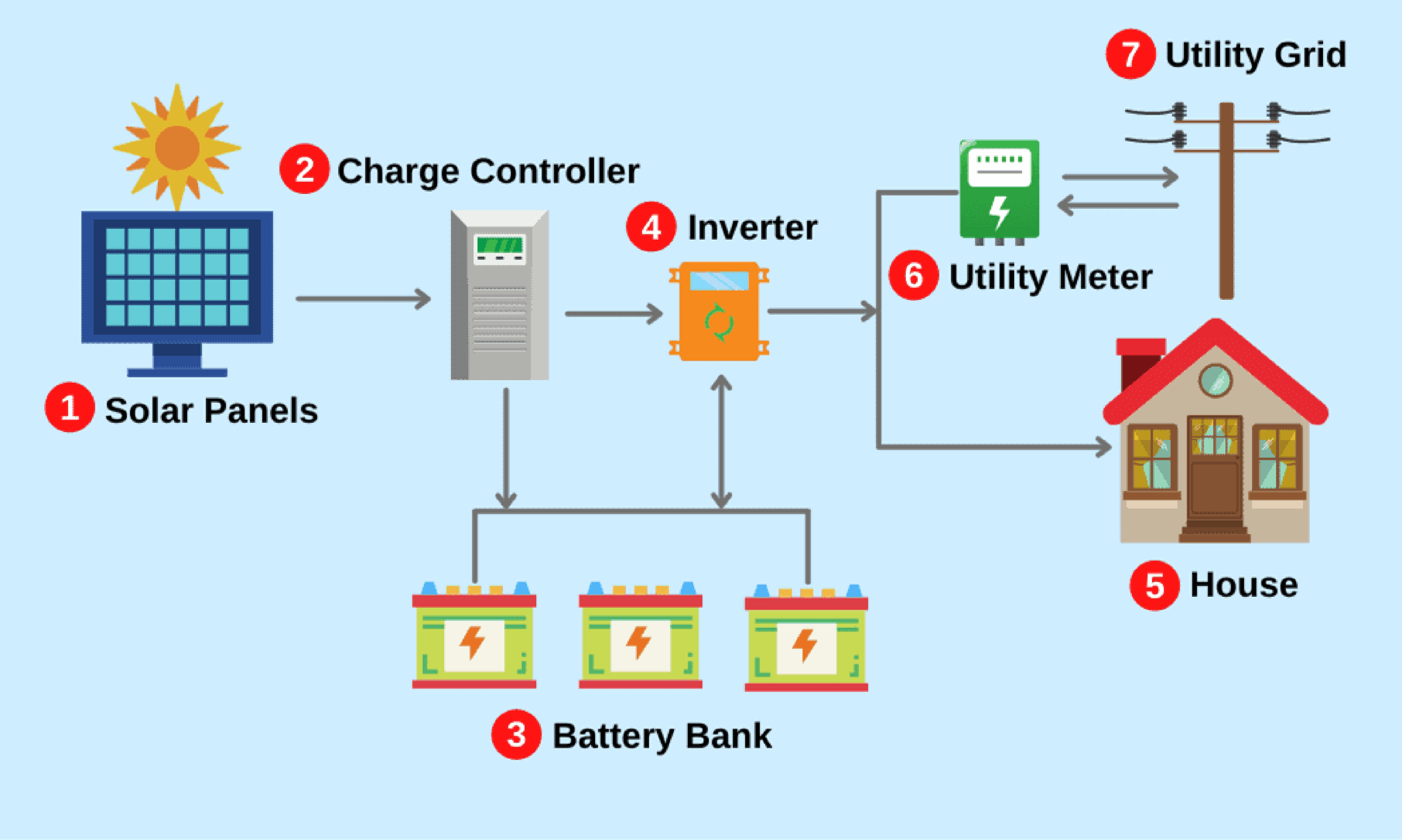
Solar Panels Convert Solar Radiation into Current



Panel made of millions of transistors.

Photons knock electrons free from transistor material, which causes a current to flow.

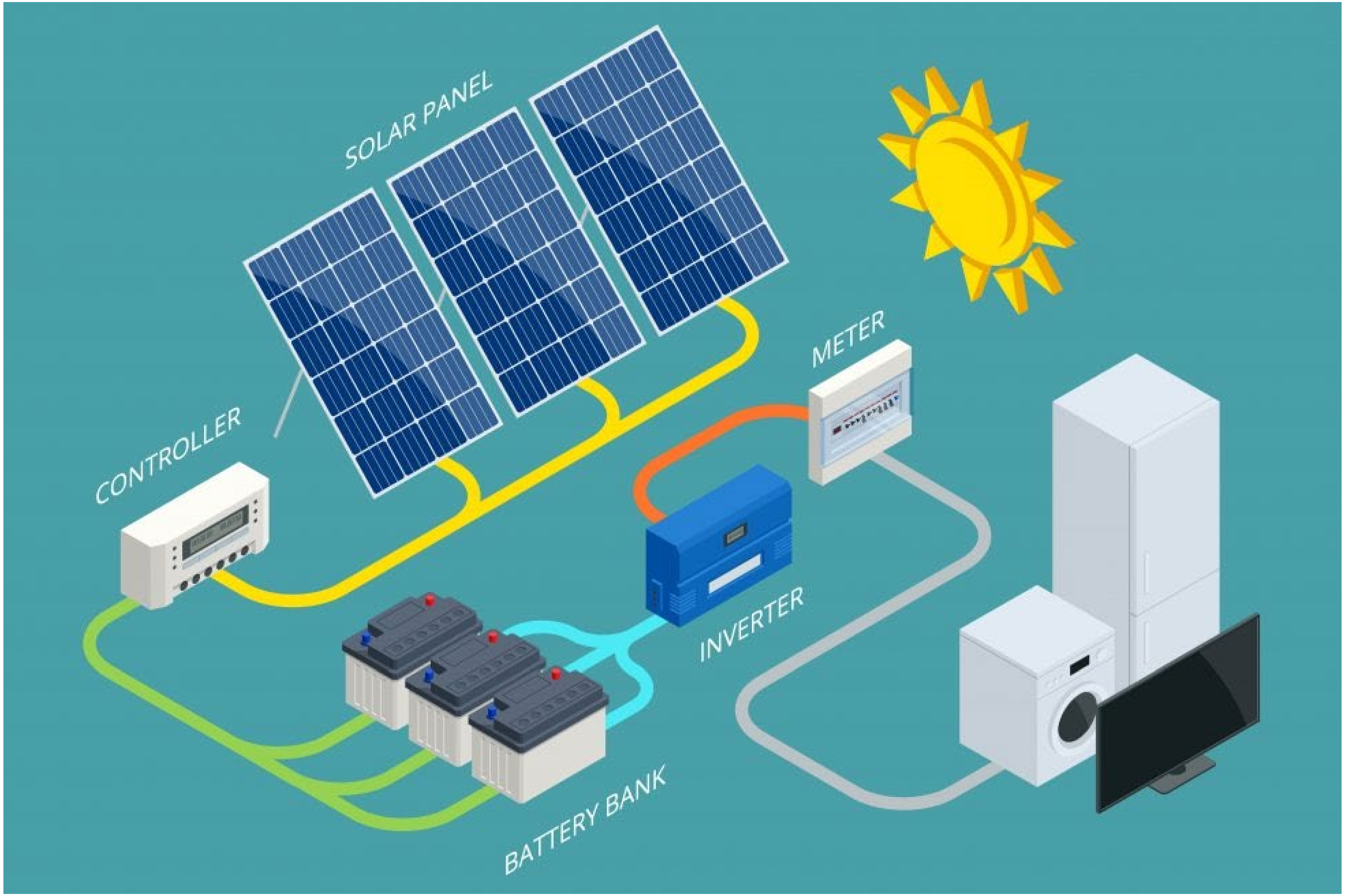
Typical Home Solar System



Components of a Home Solar System

- **Solar Panel** – converts solar radiation into current (@15-20 V)
- **Charge Controller** – converts power from solar panel to 12, 24, 36, 48… etc. volts for input to storage battery
- **Battery** – stores energy (Amp-Hours)
- **Inverter** – Converts 12 V DC into 120/240 V AC for home load
- **Smart Utility Meter** – Sends excess energy not stored into battery onto electric grid

What is the State Variable in this system?


SOLAR PANEL
CONTROLLER
METER
INVERTER
BATTERY BANK

Batteries

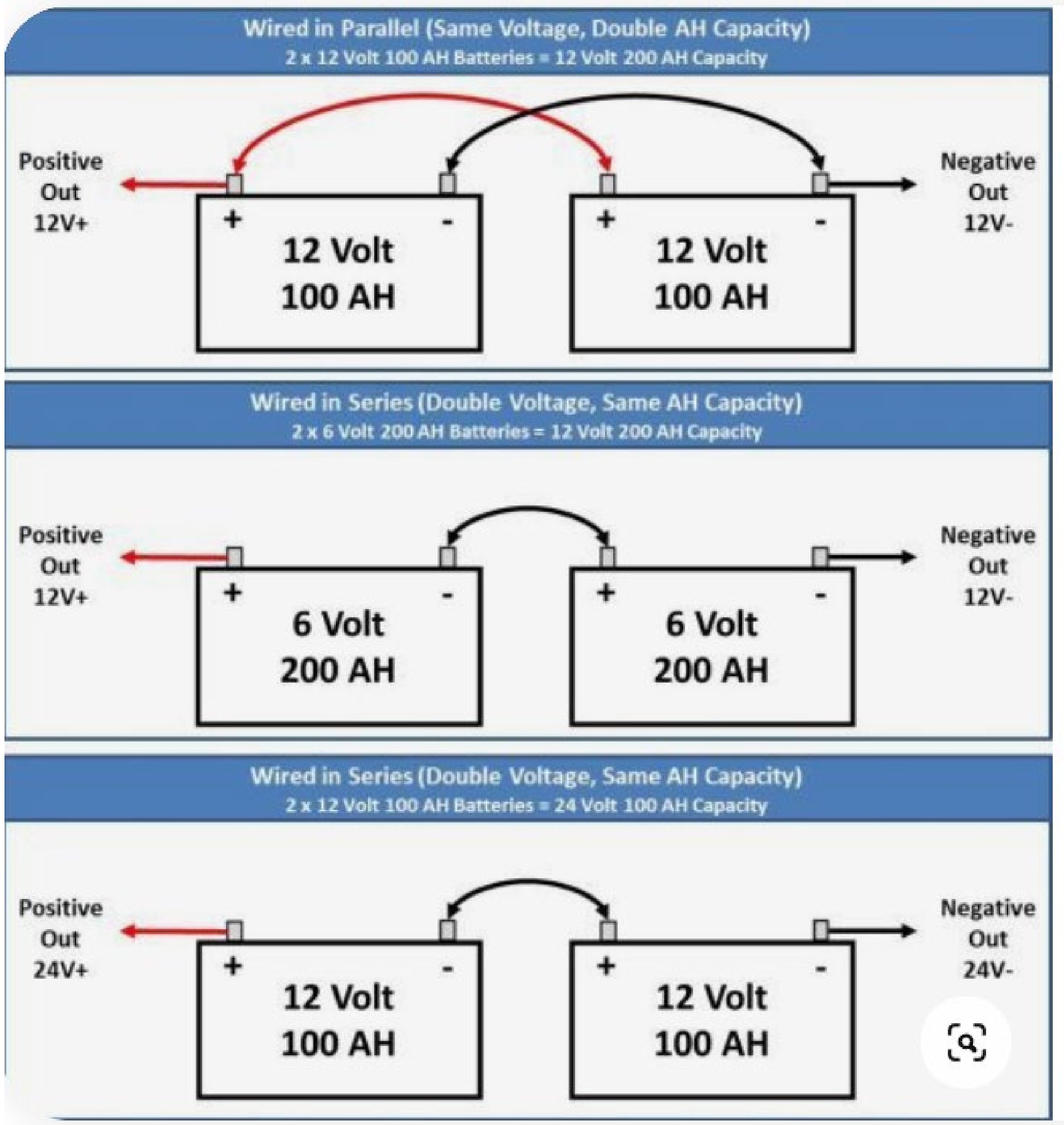
Batteries store energy as Amp-hours
Amp Hour (AH) = Current (A) x Time (H)

115 Ah

66 Ah

Bank of Batteries for Small Solar System

Series and Parallel Battery Connections



Parallel: AH add but voltage does not change
Output: 12 V and 200 AH

Series: Voltages add but AH does not change
Output: 12 V and 200 AH

Series: Voltages add but AH does not change
Output: 24 V and 100 AH

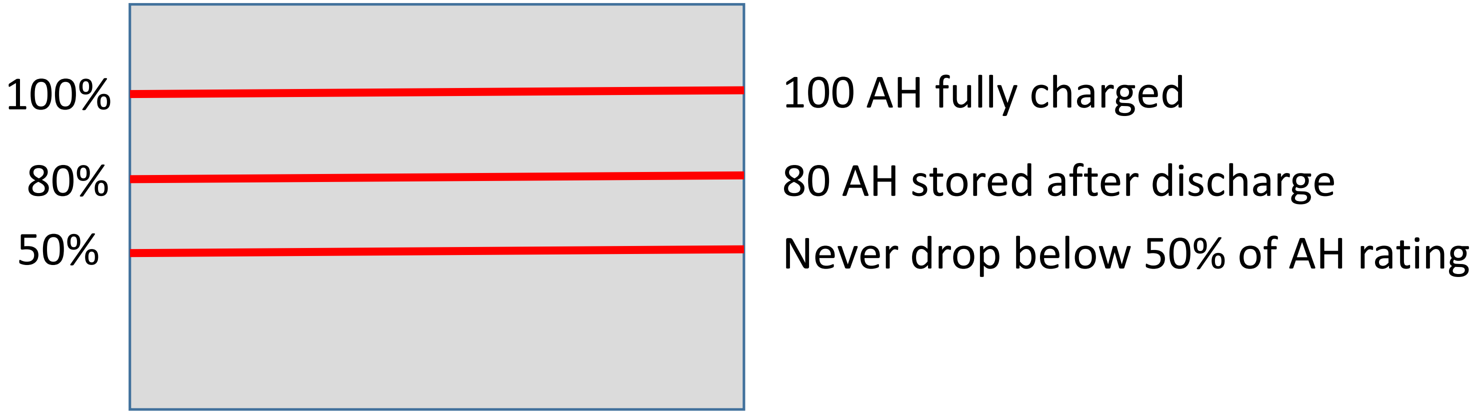
Batteries

A fully charged 100 AH battery runs a 10 amp motor for 2 hours. How many stored amp-hours (AH) are removed from the battery?

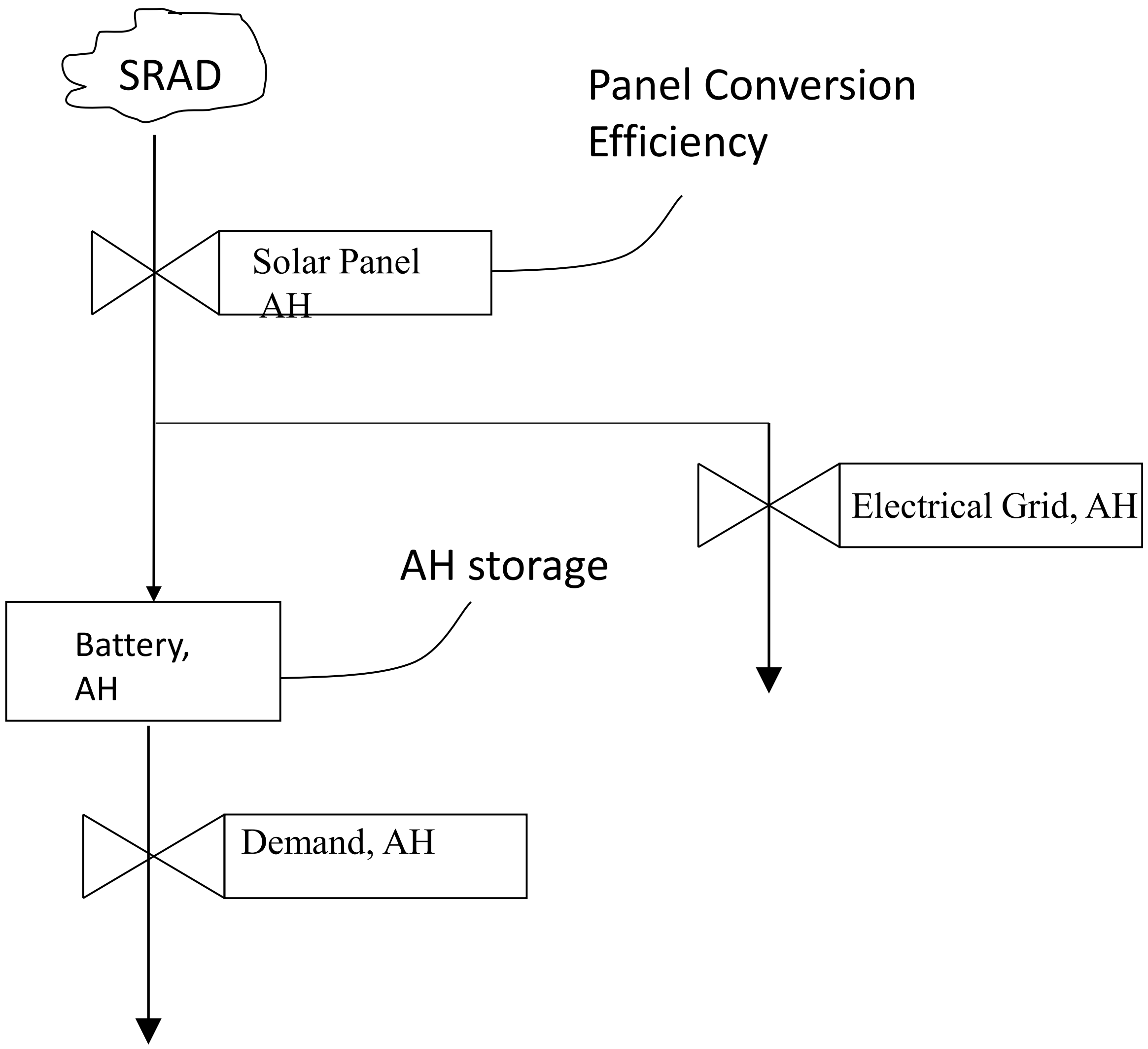
10 amps * 2 hours = 20 AH

The fully charged battery holds 100 AH. A total of 20 AH was discharged. Remaining energy in the battery is 100-20 = 80 AH

Never discharge a batter below 50% of it's AH storage capacity or the battery will be permanently damaged!



Forrester Diagram



- Input is daily solar radiation, MJ/m^2
- Rate variable equation converts MJ/m^2 to current flow at designated voltage
- Single state variable is battery storage, AH
- Demand is user input, AH
- If battery is full, power goes to grid

Useful Electricity Relationships

Voltage = Current x Resistance (E = I R)
Power = Voltage x Current (P = E I)

Voltage – volts
Resistance – ohms
Current – amps
Power - watts

Convert Solar Radiation to Watt-Hours

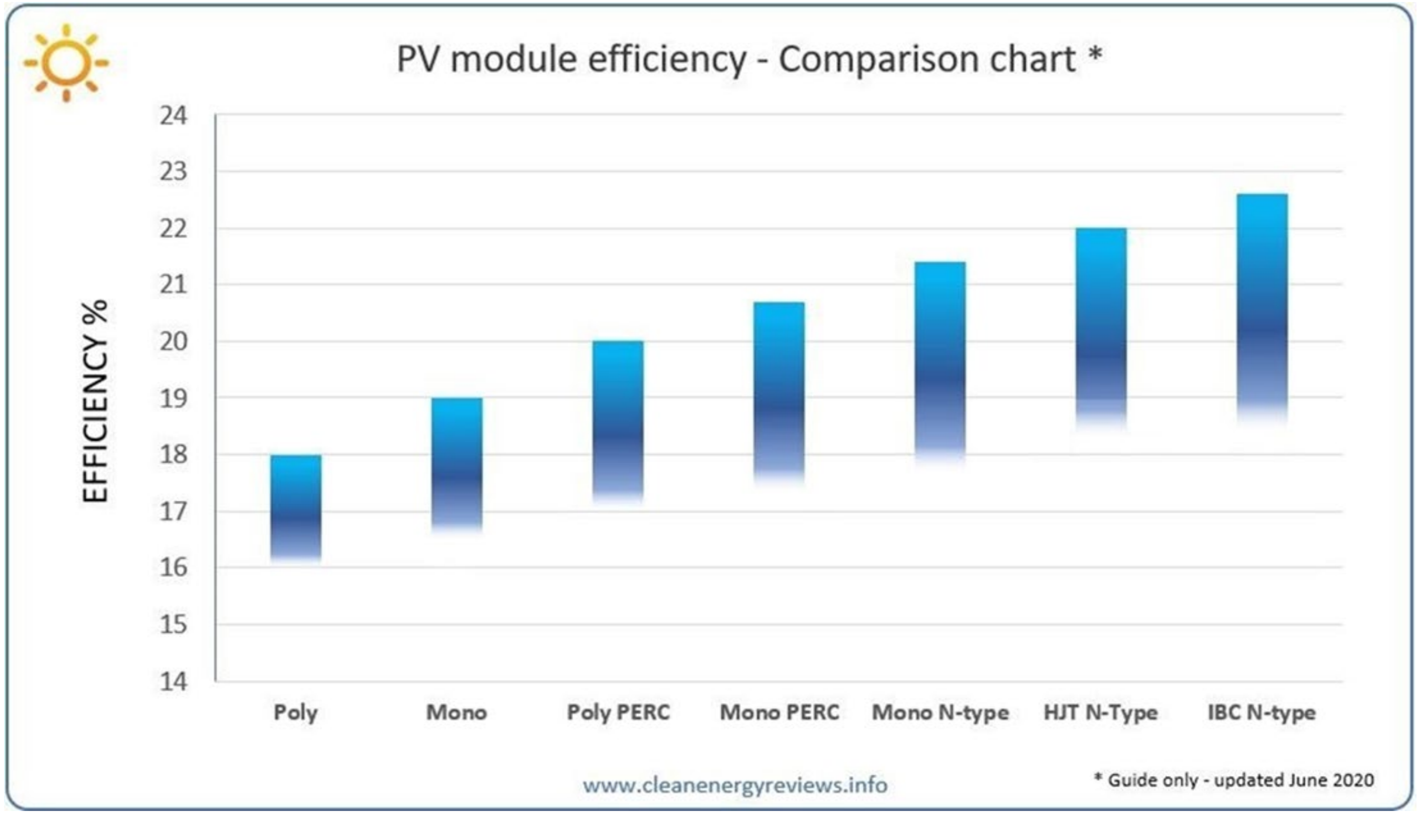
- MJ/m^2 – measure of daily solar radiation
- 1 MJ = 277.77 WH
- Obtain weather data from internet source for your location

Example: 25 MJ/m^2 of solar radiation occurs today. Compute the WH of energy.

$$\frac{25\,MJ}{m^2} * \frac{277.77\,WH}{MJ} = 6944\,W\mathrm{H}$$

Solar Panels

- Typical panel produces 100 W under perfect sunlight
- Solar panel efficiency is 16-23% at converting sunlight into electricity
- Higher efficiency means higher cost!



Case Study

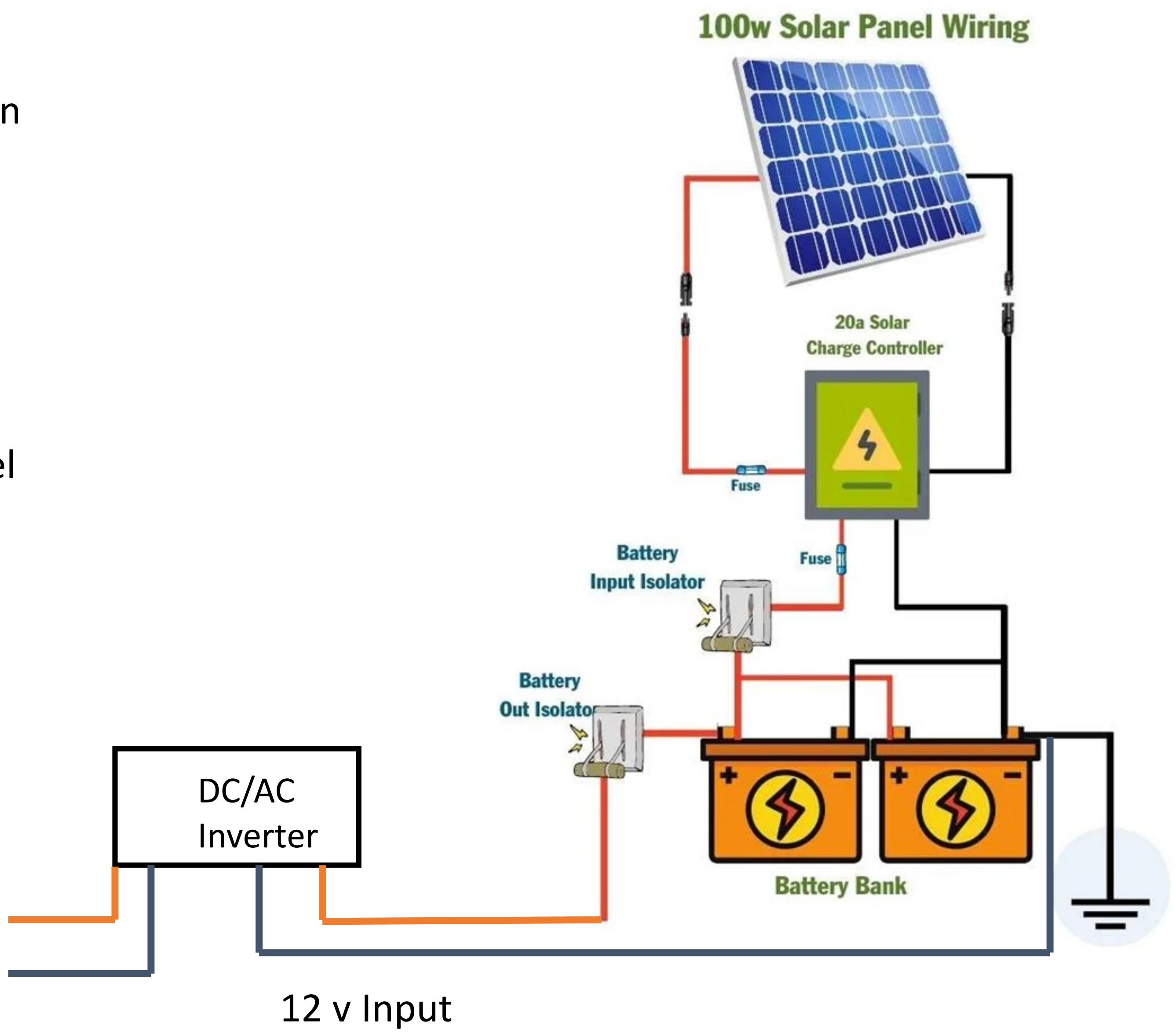
A 100 W solar panel received 25 MJ/m^2 of solar radiation on July 1. The panel has a conversion efficiency of 0.16 (ie. 16%).

The solar panel connects to a charge controller that outputs 18v to the battery.

The panel is attached to 2 batteries connected in parallel that are rated at 12 Volts and each battery stores 100 AH. This gives a combined storage of 200 AH with an output of 12 volts.

Batteries are connected to a 12v to 120v inverter to supply 120 v power to the building.

The daily load is 3 AH



Step 1: Convert Daily Energy From Sun ($MJ/m^2/day$) to WH

1 MJ = 277.77 WH

Note: WH is Watt-hours

Example: 25 MJ/m^2 of solar radiation occurs today. Compute the WH of energy.

$$\frac{25\,MJ}{m^2} * \frac{277.77\,WH}{MJ} = 6944\,WH/m^2$$

Note: The unit m^2 refers to surface area of the solar panel

Step 2: Convert WH Received by Solar Panel to Amp-hours Into Battery Bank

Solar panel outputs amps at a design voltage (typically 15-18 V)

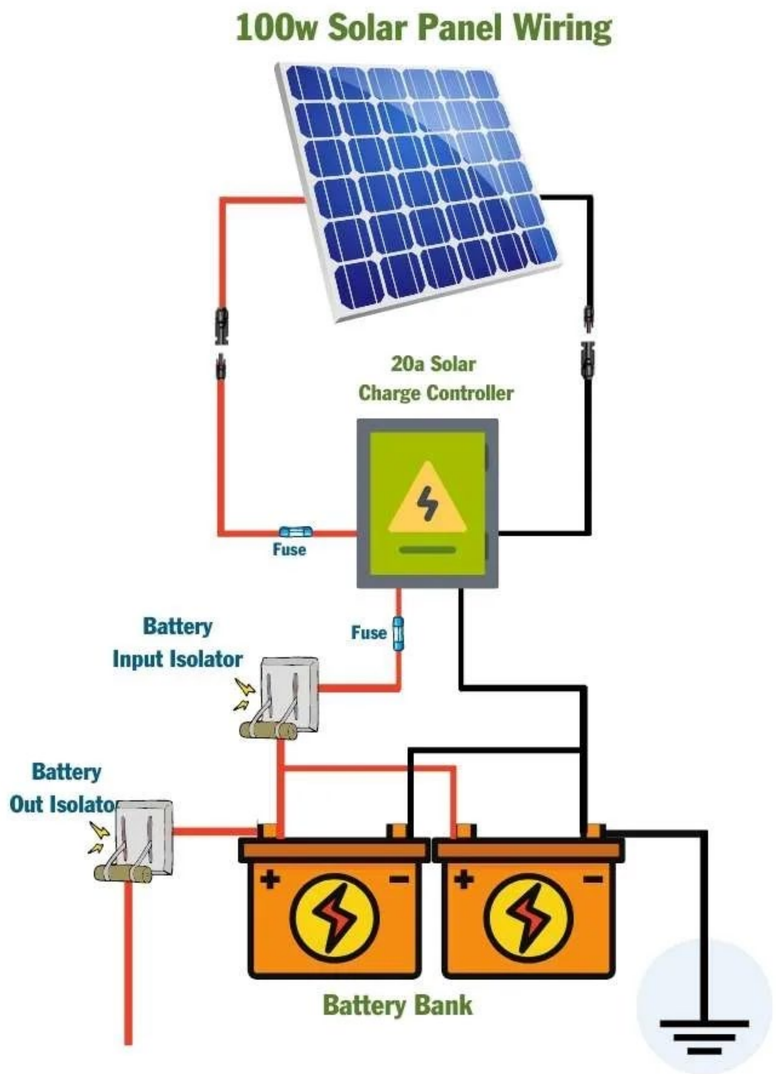
Ohm's Law: Power = Voltage x Current
Watts = Volts x Amps

Convert Power produced by panel to Amps at designated voltage

Example: A solar panel produces 6944 WH of energy from 25 MJ/m^2 of solar radiation today. The solar panel outputs the power at 18 volts. Convert WH to AH.

$$AH = \frac{WH}{V} = \frac{6944\ WH/m^2}{18\ V} = 386\ \text{AH/m}^2$$

If the panel is 100% efficient at converting solar to electrical energy, it would produce 386 AH/m^2 of electricity for this example.



Step 3: Reduce AH into Battery Due to Solar Panel Efficiency

Example: Assume the solar panel in this example has an efficiency of 16%. Convert the potential AH/m^2 into actual AH/m^2 going into the battery using the panel efficiency.

$$386\frac{AH}{m^2}\ x\ 0.16 = 62\ AH/m^2$$

Step 4: Compute AH into Battery

In this example, we have 1 solar panel that is 42” x 20” in size

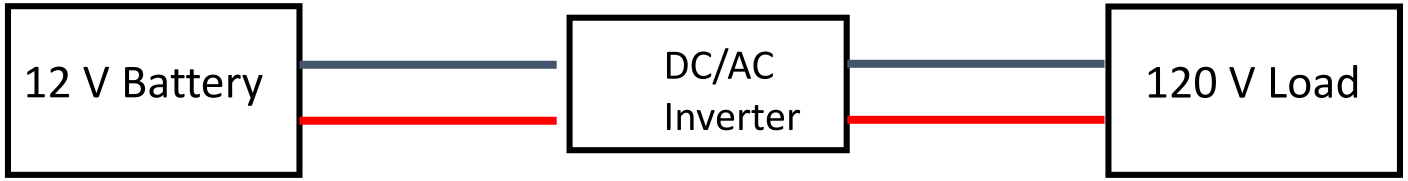
$$Area = (42" \; x \; 20") \; x \; \frac{1 \, m^2}{1550 \, in^2} = 0.54 \, m^2$$

$$Panel \; AH = 0.54 \, m^2 \; x \; 62 \frac{AH}{m^2} = 33.5 \, AH$$

If you have more than 1 panel, multiple by number of panels

Thus, a day with 25 MJ/m² of solar radiation will add 31.3 AH of storage to the battery

Step 5: Compute Battery AH Output from Daily Load



30 AH from battery

3 AH load

Power = Volts * Amps

Power leaving battery at 12 V = Power consumed by load at 120 V

Battery AH * 12 V = 3 AH * 120 V

Note: Daily load is 3 AH

Battery $AH = \frac{3\ AH * 120\ V}{12\ V}$ = 30 AH

Thus, a load of 3 AH at 120 V draws 30 AH at 12 V from the battery

Step 6: Compute Battery AH Balance

Combining Step 4 and Step 5 gives the following state variable equation for battery storage:

$$B^{t+dt} = B^t + (AH_{in}^t - AH_{out}^t)\, dt$$

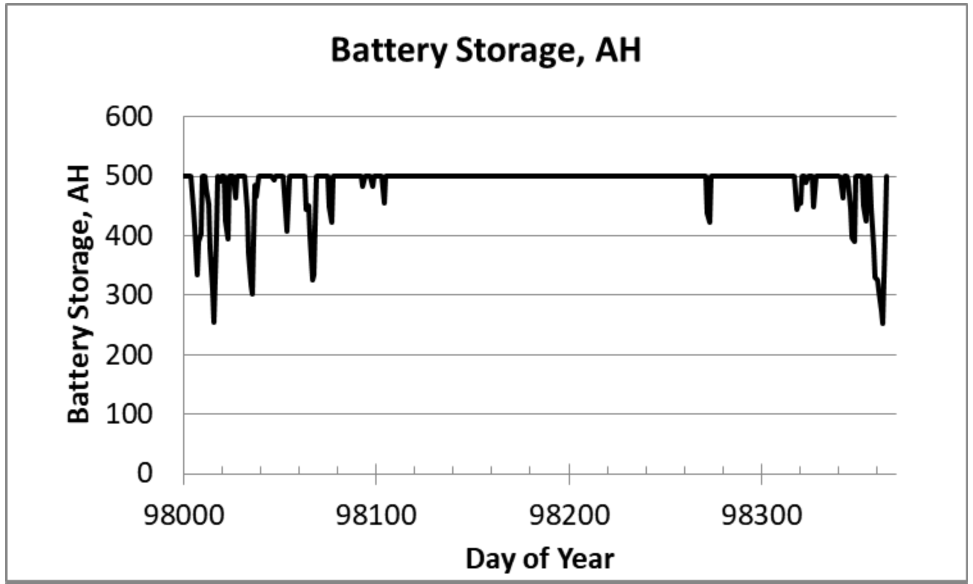
B^{t+dt} = 160 + (33.5-30) dt = 163.5 AH

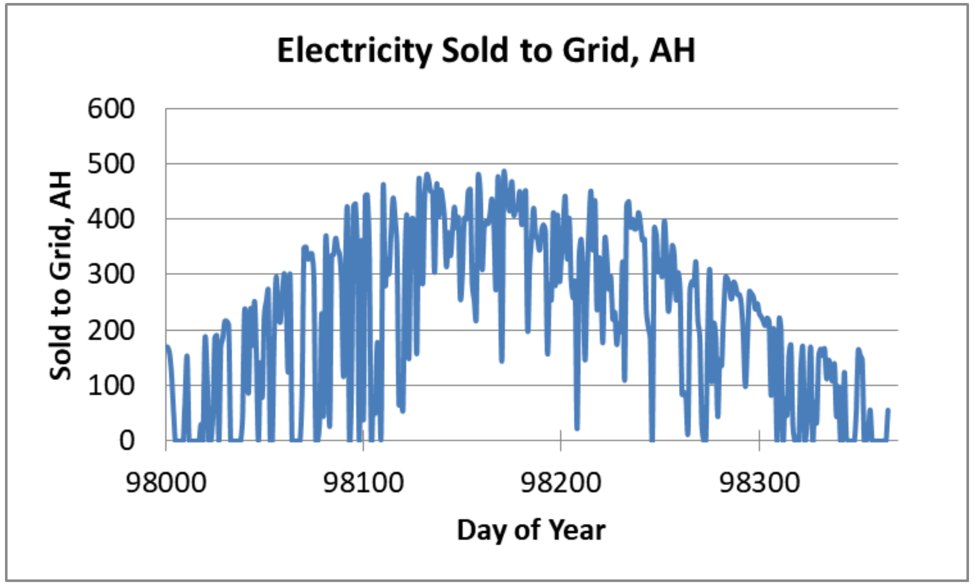
If B^{t+dt} > 200 AH then B^{t+dt} = 200 AH

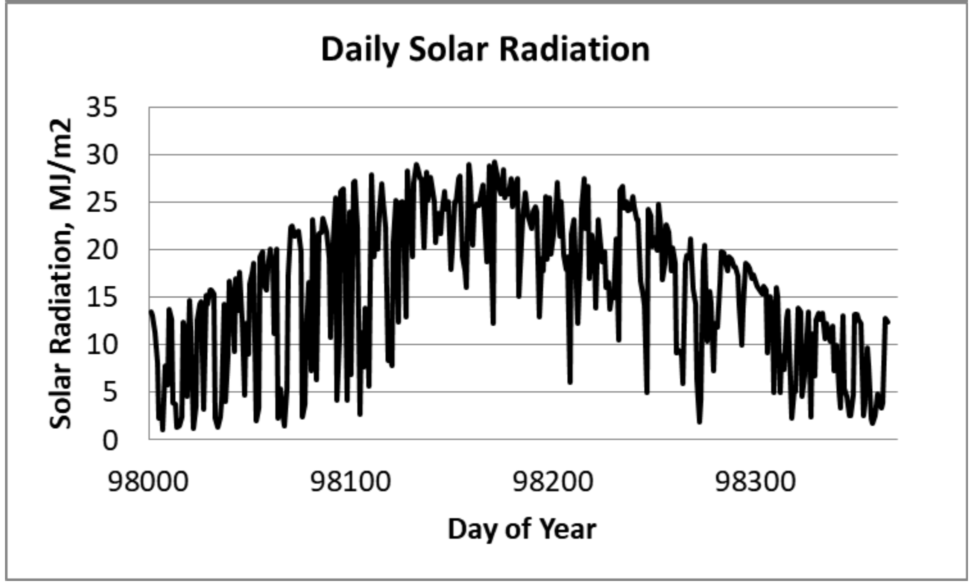
Note, The charge controller will not allow the battery bank to exceed it's rated 200 AH storage

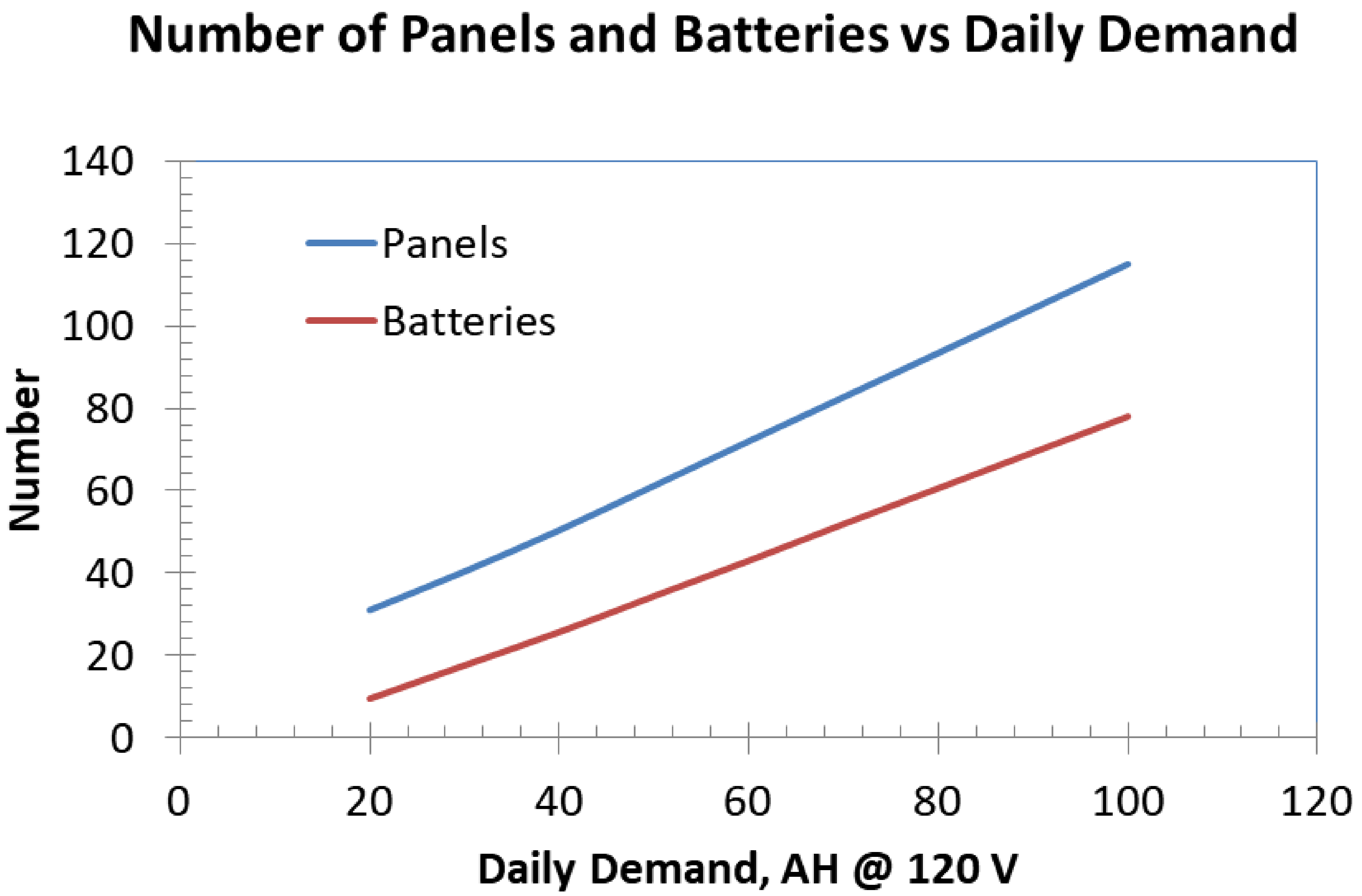
Developing a Model in Excel Spreadsheet

Area of Single Solar Panel	0.54	m2
Number of Solar Panels	15	
Panel Efficiency	0.16	
Panel Voltage	18	V
Number of Batteries	5	
Init Amp Hour Battery Storage	100	AH
Battery System Voltage	12	V








Number of Panels and Batteries vs Daily Demand
Panels
Batteries
Number
Daily Demand, AH @ 120 V
0
20
40
60
80
100
120
140

Other Considerations

- Intercepted solar radiation by panel is complex geometric algorithm
- Panel output and battery storage is sensitive to cold temperatures
- Battery bank cannot be discharged over 50% of rated capacity
- Selling electricity to grid is complex