02-Energy Fundamentals

ECEGR 4530
Renewable Energy Systems

Overview

- Energy
- Forms of Energy
- Conversion of Energy
- Efficiency
- Power
- Capacity Factor

Energy

- Energy: measured in joule (J)
  - Named after James Prescott Joule
- Derived quantity:
  - Work done by a force of 1 newton over a distance of 1 meter
  - $1\ J = 1kg \times (m^2/s^2)$
  - $1\ W = 1\ J/s$

Other common units of energy

- Depending on the context (and country) different units of energy are commonly used
- Watthour (Wh): 3600 J
  - Kilowatthour = 1000 Wh = 3.6 MJ
  - Megawatthour: 1,000,000 Wh = 3.6GJ
- Ton of Oil Equivalent = 41.8 GJ
- BTU (British Thermal Unit) = 1055 J
- Quad (quadrillion BTU): 1.050 EJ

GJ: billion joules

Energy

- Rough equivalents:
  - 1 gallon of gasoline = 130 MJ = 36.1 kWh
  - 1 pound of coal = 16 MJ = 4.44 kWh
  - 1 standard cubic foot of natural gas = 1.1 MJ = 0.31 kWh
  - 1 candy bar = 1 MJ = 0.27 kWh
  - 1 pound of fat = 4226 Calories
    - Body fat = 3500 Calories (it is not all fat)
  - A Big Mac contains about 600 Calories (2.51 MJ)

Exercise

A marathon runner "burns" 2,000 Calories during the 26.2 mile race. She completes the race in 4 hours. How many kWh does she burn?

Exercise

A marathon runner “burns” 2,000 Calories during the 26.2 mile race. She completes the race in 4 hours. How many kWh does she burn?

- 2,000 Calories = 8.36×10^6 J = 2.32 kWh

Forms of Energy

- Kinetic Energy
- Gravitational Energy
- Nuclear Energy
- Electrical Energy

Kinetic Energy

- Energy of a moving object

$$E_K = \frac{1}{2}mv^2$$

  - m: mass of the object (kg)
  - v: velocity of the object (m/s)
- Used in wind turbines, wave-powered generators and run-of-river hydro generators

Exercise

- A wind turbine converts with 30 percent efficiency the kinetic energy of the air mass that passes through its rotor area. Assume the air is traveling at a speed of 10 m/s, the density of air is 1.2 kg/m^3 and the rotor diameter is 90 m.

- How much electrical energy, in MWh, does the wind turbine produce over the course of 1 hour?

Exercise

- Mass of the air: area (m^2) x length (m) x density (kg/m^3)
  - Area: $45^2 \times \pi = 6361\ m^2$
  - Length: 10 (m/s) = 10 x 60 x 60 = 36000 m
  - Density: 1.2 kg/m^3
- Mass = 274,818,420 kg

Exercise

- Applying: $E_K = \frac{1}{2}mv^2$
  - E_k = 0.5 x 274,818,420 x 10^2 = 13.7 GJ
- Accounting for efficiency: 0.3 x 13.7 GJ = 4.11 GJ
- Converting to MWh:

  4.11 GJ/3600(MJ/MWh) = 1.15 MWh

Kinetic Energy

- Kinetic Energy within a body is thermal energy
- Temperature: measure of the average thermal energy in a system
- A cup of tea can have a higher temperature than a cool lake, but the lake will have a higher amount of thermal energy

Kinetic Energy

- Standard Units of temperature
  - $T(^{O}C) = T(K) - 273.15$
  - $T(^{O}F) = 1.8T(^{O}C) + 32$
- Where:
  - T: temperature
  - K: Kelvin
  - ^{O}C: Celsius
  - ^{O}F: Fahrenheit

Kinetic Energy

- Temperature and heat are related by specific heat and mass of a substance

$$\frac{\Delta Q}{\Delta T} = mc_h$$

- Where:
  - c_h :specific heat (J/(K-kg))
  - ΔQ: change in heat (J)
  - ΔT: change in temperature (K)

Note: temperature must be in K

Example

- You plan on using large mirrors to reflect sun light onto a container to heat your shower water. You will use 30 liters of water in your shower at a temperature of 120 degrees F. The unheated water is at 60 degrees F.

- How much energy must you apply to the water? Ignore the presence of the container for your calculation.
  - Note: 1L of water weighs 1 kg
  - Note: specific heat of water is 4186 J/(K-kg)

Example

- First convert to K
  - 120 ^oF = 322 K
  - 60 ^oF = 289 K
- Mass of the water: 30 kg (1 liter weighs 1 kg)
- Now apply: $\Delta Q = \Delta T m c_h$
  - ΔQ = (322 – 289) x 30 x 4186 = 4.14 MJ = 1.15 kWh

Kinetic Energy

- Additional heat is required to fuse or vaporize a substance
  - latent heat of fusion
  - latent heat of vaporization
- Thermal energy is used in solar thermal generation, geothermal generation

Gravitational Energy

- Potential Energy
  $E_P = mgh$
- Where:
  - m: mass of the object (kg)
  - g: acceleration caused by gravity (9.8 m/s^2)
  - h: height (head) of the object (m)
- Gravitational energy is used in tidal generation and impoundment hydro generation

Exercise

Assuming an operating head height of 89 m and a efficiency of 70 percent, how many cubic meters of water are needed to generate 1 MWh of electricity?

Note: 1 cubic meter of water weighs 1000 kg

Exercise

Assuming an operating head height of 89 m and a turbine/generator efficiency of 70 percent, how many cubic meters of water are needed to generate 1 MWh of electricity?

From equation for potential energy:

$$1\text{MWh} = 1\text{x}10^6\text{x}60\text{x}60 = 3.6\text{x}10^9 \text{ joules}$$

$$E = mgh\eta \text{ (in joules)}$$

$$3.6\text{x}10^9 = m\text{x}9.8\text{x}89\text{x}0.70$$

$$m = 5.9\text{x}10^6\text{kg}$$

Mass of water needed

$$v = \frac{m}{1000} = 5.9\text{x}10^3 \text{ cubic meters}$$

1 cubic meter weighs 1000 kg

Nuclear Energy

- Energy bound up in the nucleus of an atom

$E_N = mc^2$

- Where:
  - m: mass of the object (kg)
  - c: speed of light (3.8 x 10^2 m/s)
- Nuclear fission is used in nuclear power plants

Electrical Energy

- Energy that exists between two charged particles

$$E_E = k_c \frac{q_1 q_2}{r}$$

- Where:
  - q_x: charge of particle, 1.6 x 10^{-19} (C)
  - k_c: Coulomb's Constant 8.98 x 10^{-9} (Nm^2/C^2)
  - r: distance between the particles (m)

Electrical Energy

- As atoms form molecules, their electrons often redistribute and potential electric energy increases
- Burning the chemical releases the energy
  - chemical energy
- Electromagnetic energy is a form of electrical energy, it is the energy carried by electromagnetic radiation

Conversion of Energy

- Conversion of energy is governed by the 1st and 2nd laws of thermodynamics
  - Conservation of energy
  - Entropy increases

Conversion of Energy

- First Law of Thermodynamics:

$$\Delta E = Q - W$$

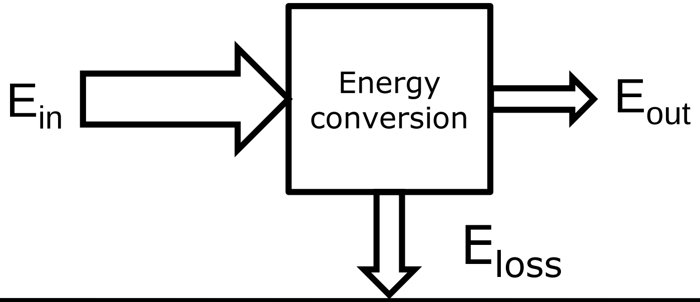
- Where
  - ΔE: change in internal energy of a system (J)
  - Q: heat transfer (J)
  - W: work done (J)
- Q is positive when heat enters the system

Energy Efficiency

- No conversion process is 100% efficient
- Losses always present

$$\eta = \frac{E_{out}}{E_{in}} \times 100$$

  - η: efficiency (%)
  - E_{out}: output energy (J)
  - E_{in}: input energy (J)



Exercise

- The area of a solar panel is (1480mm x 670mm). If the solar irradiance on the panel is 1000 W/m^2, then the power output is 110W.

- What is the efficiency of the panel?

Exercise

- What is the efficiency of the panel?
- Area = 1.480 x 0.670 = 0.99 m^2
- After one second: E_{in} = 1000 J
- E_{out} = 110 J
- η = 100x (110/1000) = 11%

} Note: efficiency can be computed using power

Energy Efficiency

- A 1 Ohm heater is connected to a 12 volt battery with an internal 1 Ohm resistance.
- What is the efficiency of the heater?

Power

- Power is the derivative of energy with respect to time

$$P = \frac{dE}{dt}$$

- Where:
  - E: energy (J)
  - t: time (s)
- Rate of energy change
- Unit of power is watt (W)

Power

- Common conversions
  - 1 kW = 1,000 watts
  - 1 MW = 1,000,000 watts
  - 1 horsepower (electric) = 746 watts

Example

- A marathon runner "burns" 2,000 Calories during the 26.2 mile race. She completes the race in 4 hours. What is her average power output?

Example

- A marathon runner "burns" 2,000 Calories during the 26.2 mile race. She completes the race in 4 hours. What is her average power output?

  Solution: 2,000 Calories = 8.36×10^6 J = 2.32 kWh.
  Her average power is 2320/4 = 580 W.

Power

- In this class, we are interested in electrical power
  - Instantaneous power: p(t) = i(t)v(t)
    - i(t): current at time t
    - v(t): voltage at time t
    - p(t): power at time t
  - Average power: $P = \frac{1}{T}\int i(t)v(t)\,dt$
    - Also, if voltage and current are sinusoidal then the power through a resistor is:
    - P = IV

      I: RMS value of current

      V: RMS value of voltage

Power and Energy

- The terms “power” and “energy” are commonly used interchangeably
- This can cause confusion, especially in renewable energy systems

Power and Energy

- A 10 kW continuous electrical load is connected to the electrical grid and a 2 kW PV array.
- Can the owner rightfully claim that 20% of the load is supplied by renewable energy?
  - No.
  - The PV will only produce power when the sun is shining on it

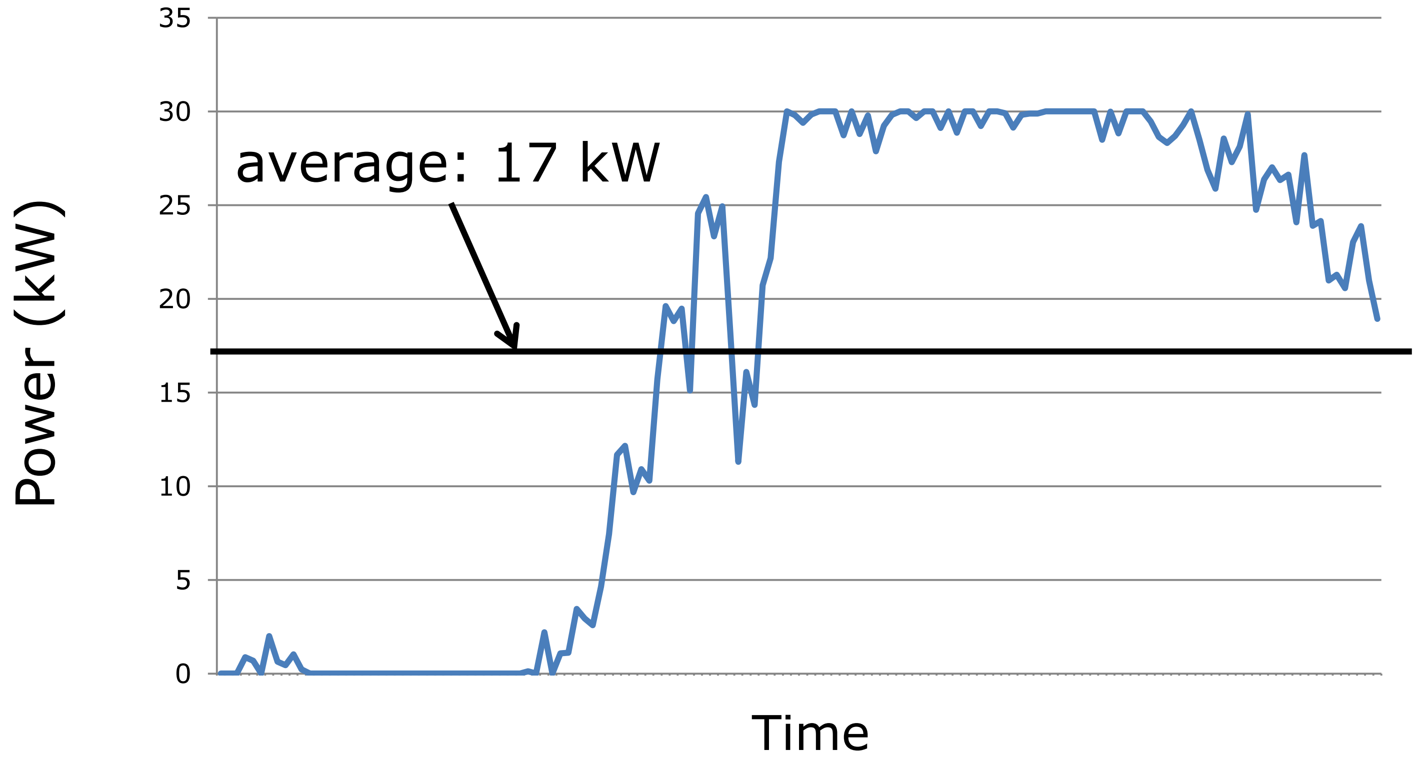
Capacity Factor

- A 2kW PV over the course of a day might only produce 9.6 kWh of energy due to sunset, clouds, angle of the sun, etc
- If the sun was shining overhead 24 hours a day, then E = 2 kW x 24 = 48 kWh
- The ratio between average energy generated over a period of time to the theoretical maximum energy generated over that time is known as the capacity factor

Capacity Factor

- $CF = E_{actual}/E_{theory}$
  - CF: capacity factor (usually expressed in %)
  - E_{actual}: actual energy produced over H hours (MWh)
  - E_{theory}: maximum theoretical energy produced over H hours (MWh)
- $E_{theory} = C \times H$
  - C: Rated capacity of the generator (MW)

Capacity Factor



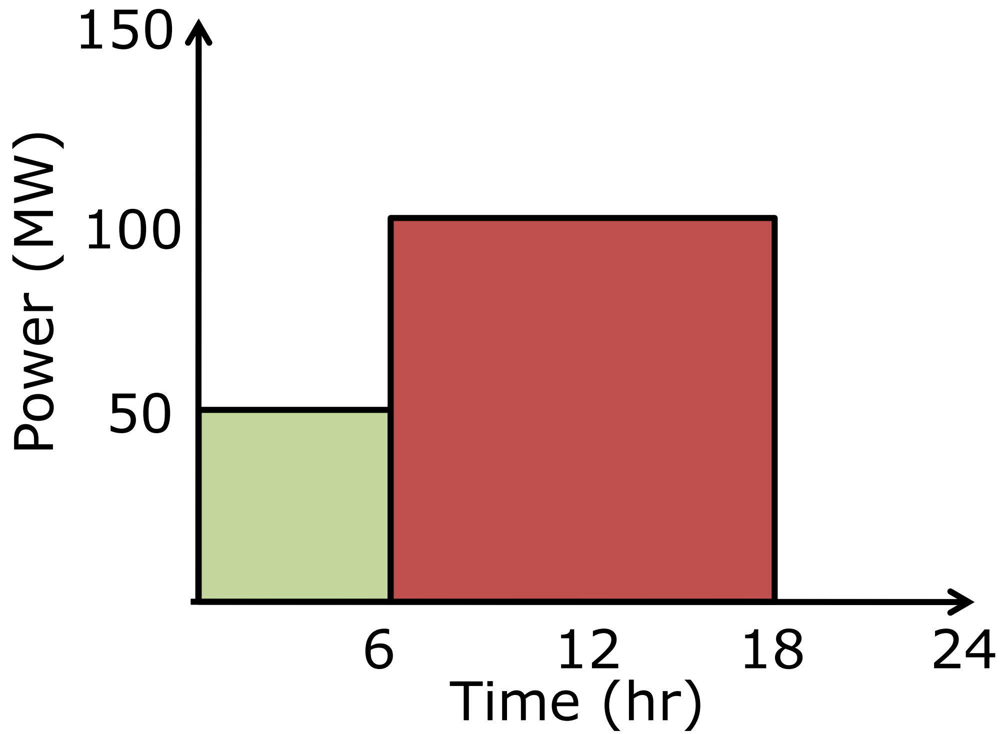
Capacity Factor: 57%

Capacity Factor

- Typical lengths of time are:
  - Lifetime of the plant
  - Year
  - Day
- In the PV example:
  - CF = 9.6 kWh /48 kWh = 0.20 = 20%

Exercise

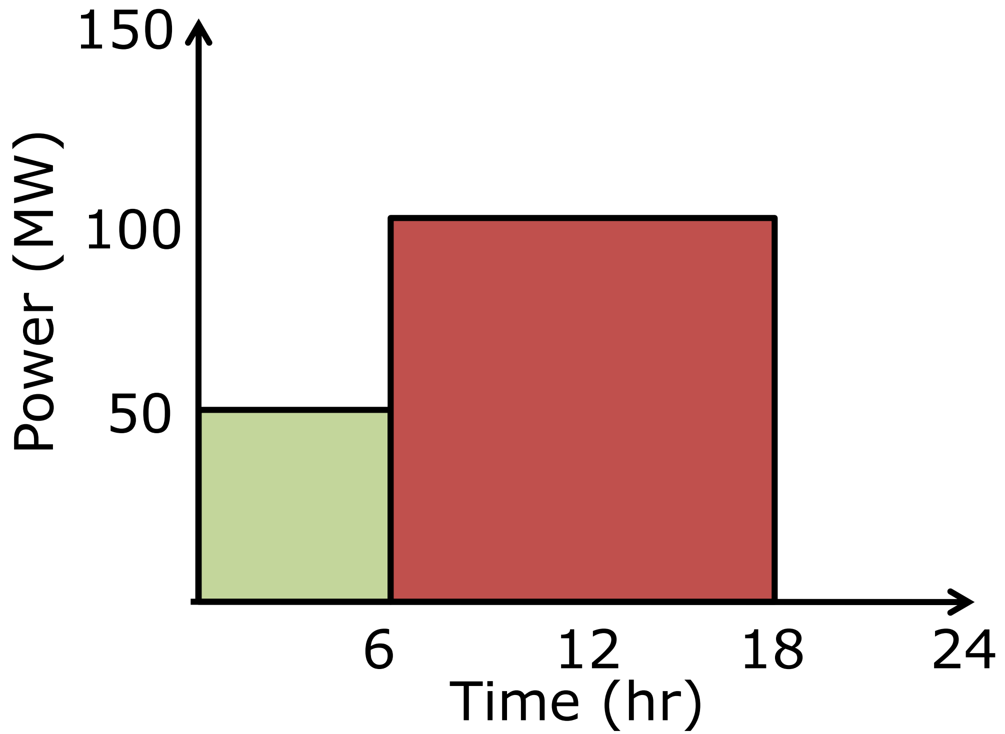
A 150 MW wind plant produces the following output. Find its capacity factor for the day.



Exercise

CF = (50 x 6 + 100 x 12)/(24 x 150) = 0.417

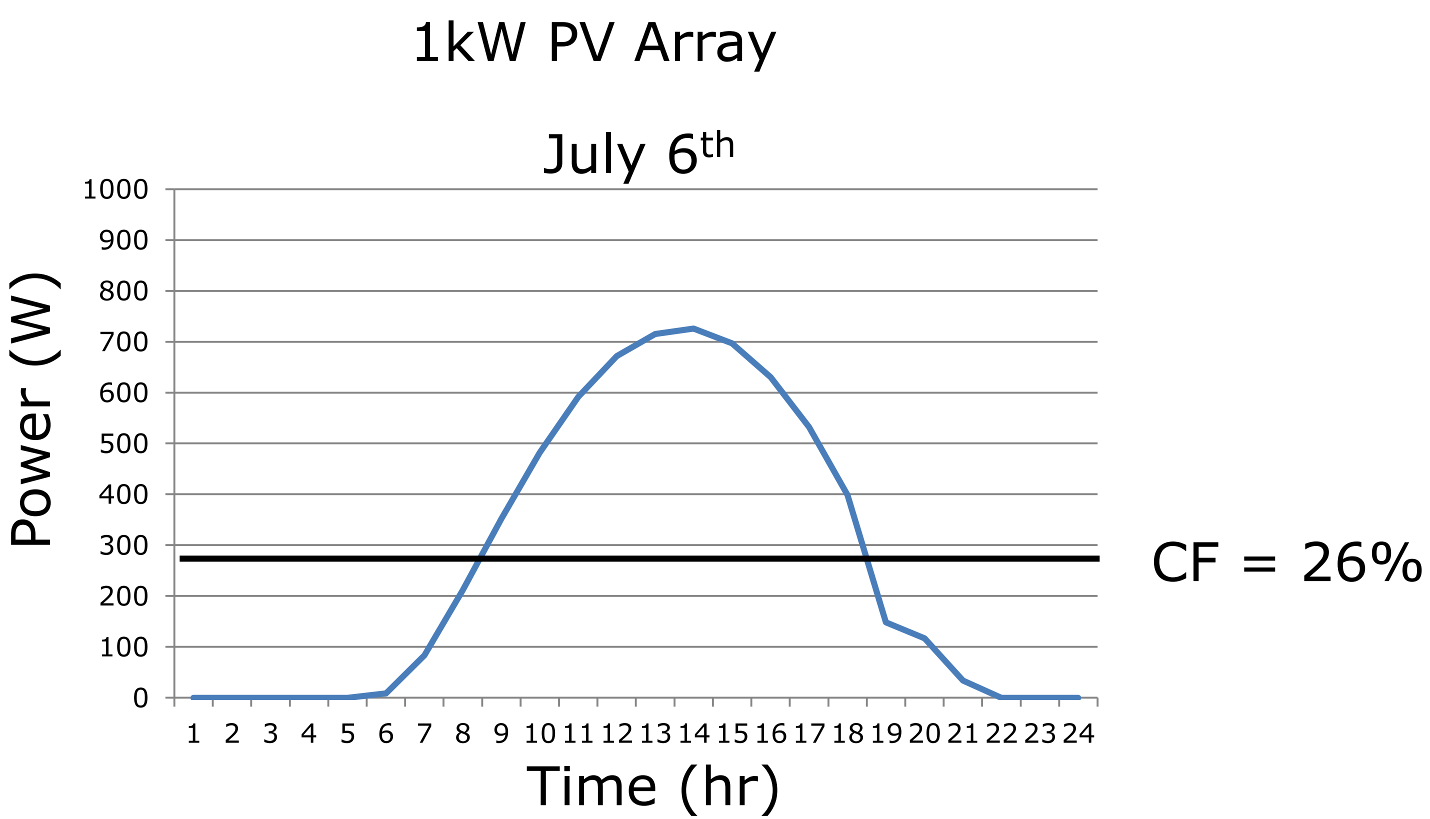
- Capacity factor of 41.7%



Capacity Factor

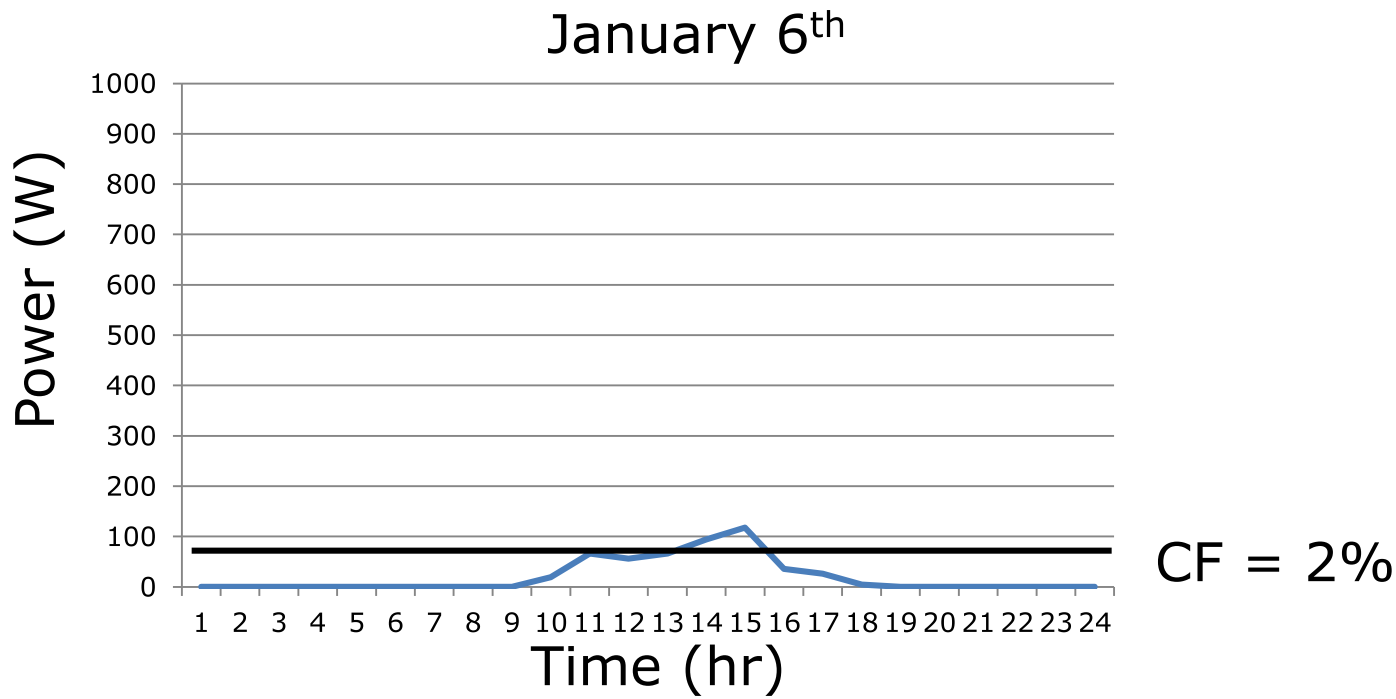
- Capacity factors vary substantially for different renewable energy systems
  - Wind: 20-40%
  - Solar: 10-25%
  - Hydro: 50-80%
- Capacity Factors often have seasonal variations

Capacity Factor



Capacity Factor

1kW PV Array



Exercise

- In 2008, wind plants in the US supplied 52 Million MWh of energy. The total installed wind plant capacity was approximately 25,000 MW.

- What is the average capacity factor of the wind plants in the US?

Exercise

- E_{actual} = 52 x 10^6 MWh
- E_{theory} = 25 x 10^3 MWh x 8760 = 219 x 10^6 MWh

- CF = 52/219 = 23.7%
  - Note: this is an underestimation because the 25,000 MW was the year-end total

Questions

- How would you respond to a friend’s proposal to collect the kinetic energy of rain drops by using piezoelectric devices?

- Is it possible to use a solar panel to power a lamp that in turn powers the solar panel?

- Why are investors of renewable energy projects interested in the project’s estimated capacity factor?