

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
 - $1 \text{ J} = 1 \text{ kg} \times (\text{m}^2/\text{s}^2)$
 - $1 \text{ W} = 1 \text{ J/s}$

→ 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

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- 2,000 Calories = $8.36 \times 10^6 \text{ J}$ = 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: $45^2 \times \pi = 6361 \text{ m}^2$
 - Length: $10 \text{ (m/s)} = 10 \times 60 \times 60 = 36000 \text{ m}$
 - Density: $1.2 \text{ kg}/\text{m}^3$
- Mass = 274,818,420 kg

Exercise

- Applying: $E_k = \frac{1}{2}mv^2$
 - $E_k = 0.5 \times 274,818,420 \times 10^2 = 13.7 \text{ GJ}$
- Accounting for efficiency: $0.3 \times 13.7 \text{ GJ} = 4.11 \text{ GJ}$
- Converting to MWh:
 $4.11 \text{ GJ}/3600(\text{MJ/MWh}) = 1.15 \text{ MWh}$

→ 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
 - $T(^{\circ}\text{C}) = T(\text{K}) - 273.15$
 - $T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32$
- Where:
 - T: temperature
 - K: Kelvin
 - $^{\circ}\text{C}$: Celsius
 - $^{\circ}\text{F}$: 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 $4186 \text{ J}/(\text{K}\cdot\text{kg})$

→ Example

- First convert to K
 - $120\text{ }^{\circ}\text{F} = 322\text{ K}$
 - $60\text{ }^{\circ}\text{F} = 289\text{ K}$
- Mass of the water: 30 kg (1 liter weighs 1 kg)
- Now apply: $\Delta Q = \Delta Tmc_h$
 - $\Delta Q = (322 - 289) \times 30 \times 4186 = 4.14\text{ MJ} = 1.15\text{ kWh}$

→ 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/s²)
- 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 an 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

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From equation for potential energy:

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

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

$$3.6 \times 10^9 = m \times 9.8 \times 89 \times 0.70$$

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

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

Mass of water needed

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 (3.8×10^2 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, 1.6×10^{-19} (C)
 - k_c : Coulomb's Constant 8.98×10^{-9} (Nm²/C²)
 - 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**

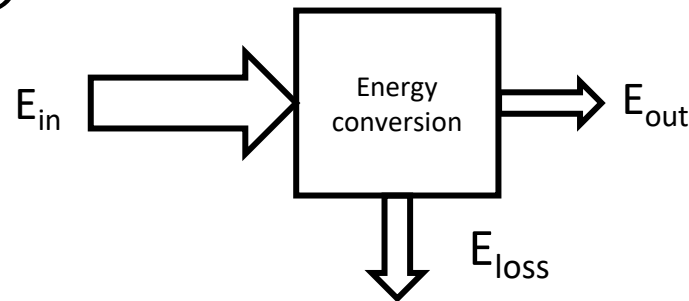
- ΔE : change in internal energy of a system (J)
 - Q : heat transfer (J)
 - W : work done (J)
- Q is positive when heat enters the system

→ Energy Efficiency

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

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

- 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 = $1.480 \times 0.670 = 0.99 \text{ m}^2$
- After one second: $E_{\text{in}} = 1000 \text{ J}$
- $E_{\text{out}} = 110 \text{ J}$
- $\eta = 100 \times (110/1000) = 11\%$ } 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

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Solution: 2,000 Calories = $8.36 \times 10^6 \text{ J}$ = 2.32 kWh. Her average power is $2320/4 = 580 \text{ W}$.

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

$$P = \frac{1}{T} \int i(t)v(t) dt$$

- Average power:

- 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

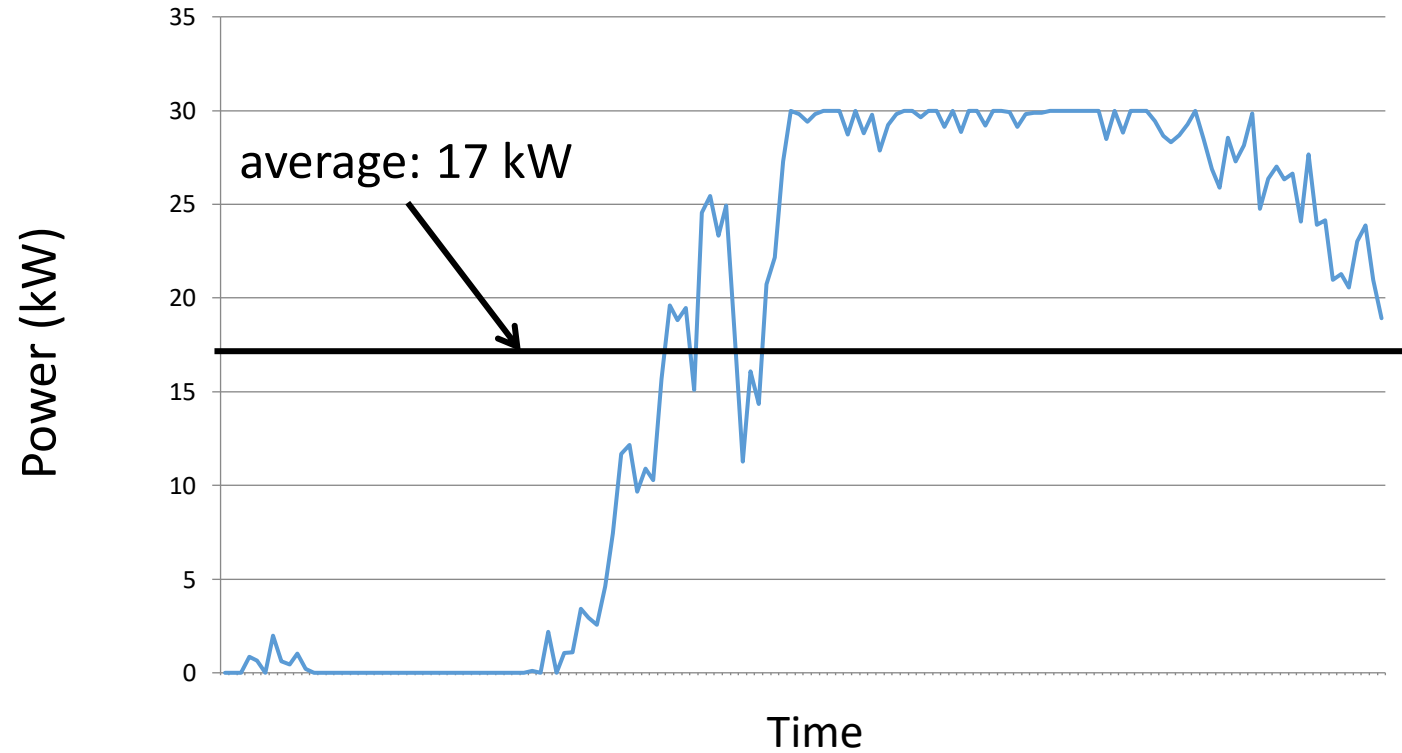
Capacity Factor

- 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 $E = 2 \text{ kW} \times 24 = 48 \text{ kWh}$
- 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

- $CF = E_{\text{actual}}/E_{\text{theory}}$
 - 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)
- $E_{\text{theory}} = C \times H$
 - C: Rated capacity of the generator (MW)

Capacity Factor



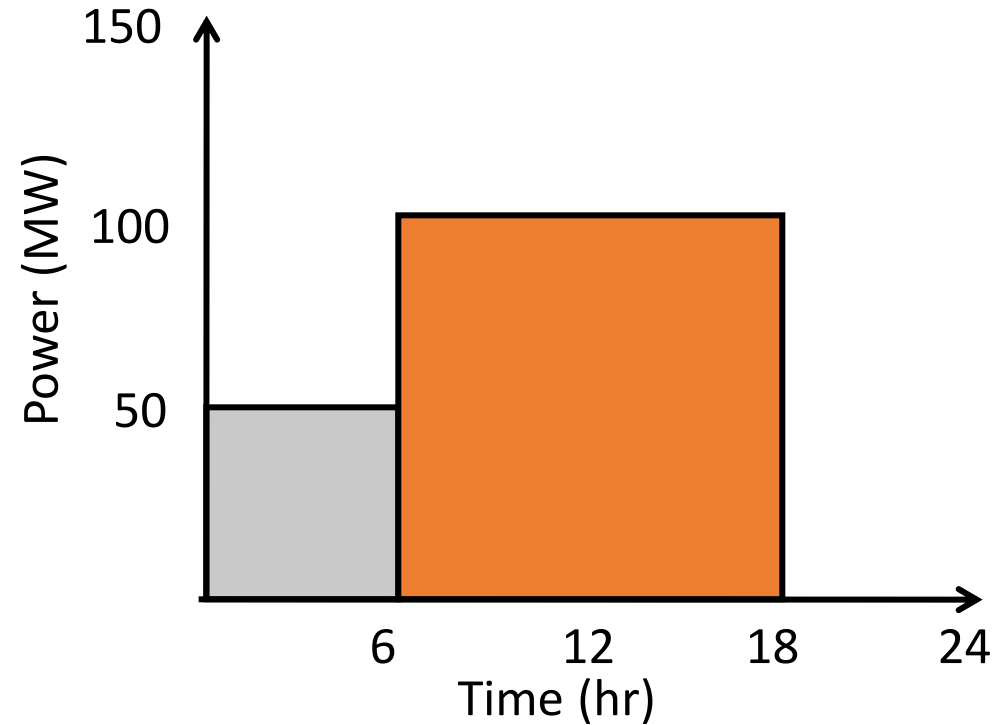
Capacity Factor: 57%

Capacity Factor

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

Exercise

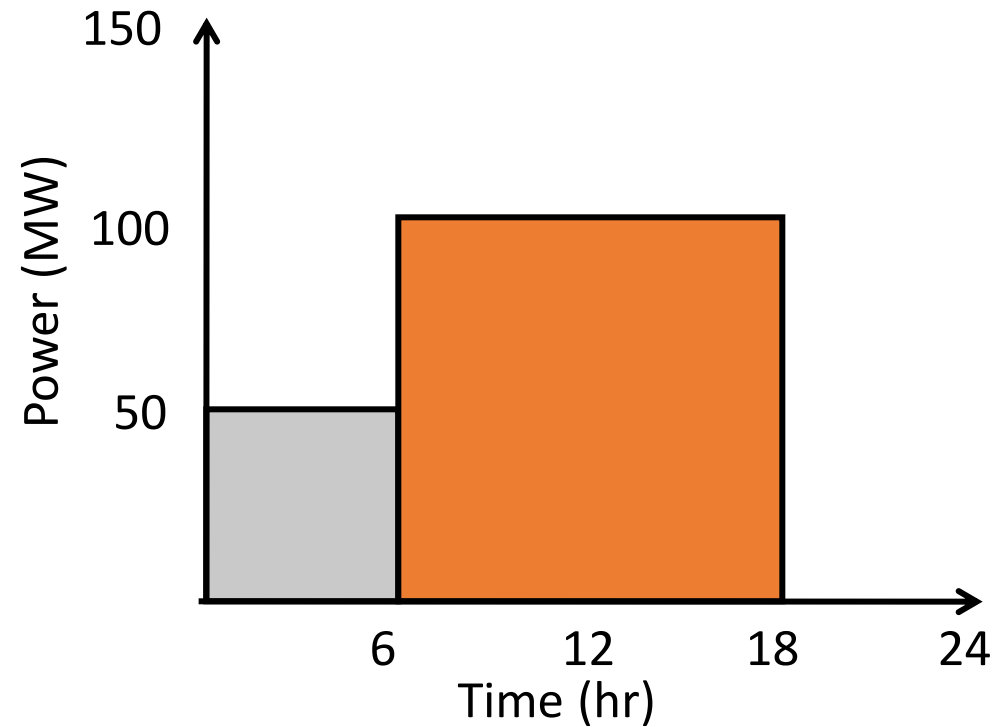
A 150 MW wind plant produces the following output. Find its capacity factor for the day.



Exercise

$$CF = (50 \times 6 + 100 \times 12) / (24 \times 150) = 0.417$$

- Capacity factor of 41.7%



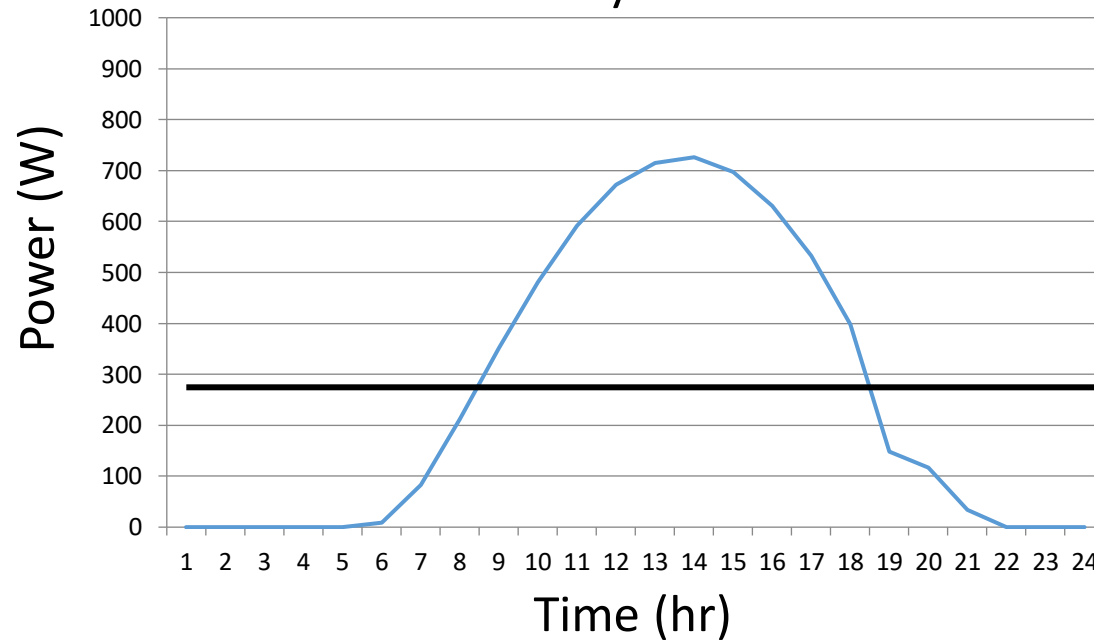
Capacity Factor

- 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

1kW PV Array

July 6th

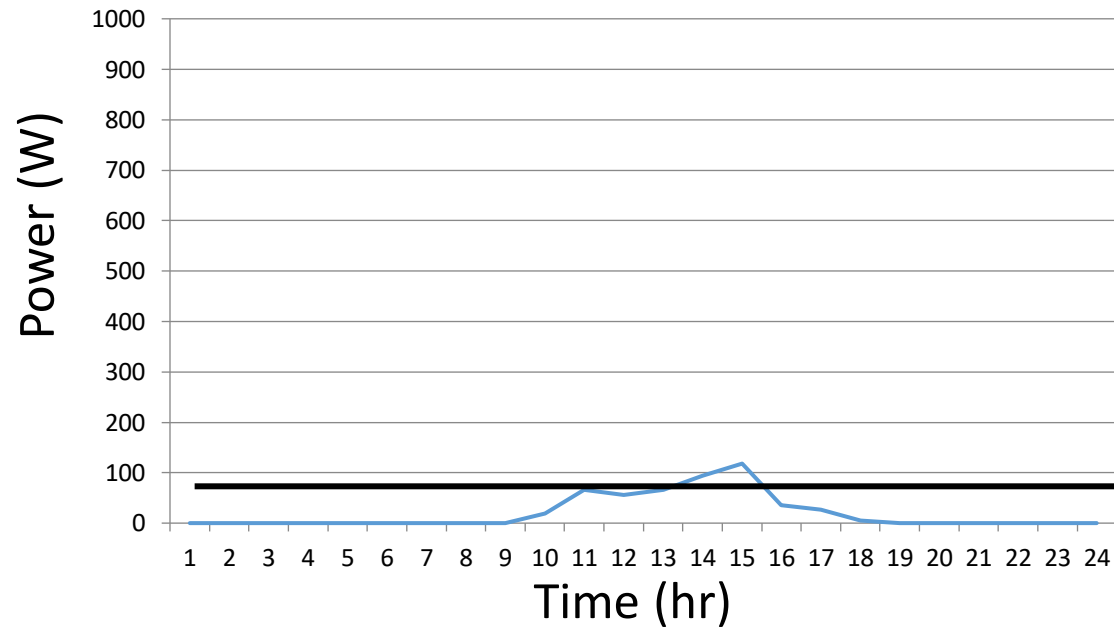


CF = 26%

Capacity Factor

1kW PV Array

January 6th



CF = 2%

» 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

- $E_{\text{actual}} = 52 \times 10^6 \text{ MWh}$
- $E_{\text{theory}} = 25 \times 10^3 \text{ MWh} \times 8760 = 219 \times 10^6 \text{ MWh}$
- $CF = 52/219 = 23.7\%$
 - 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?