NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Conventional and Renewable Generation

Conventional Power Generation Systems

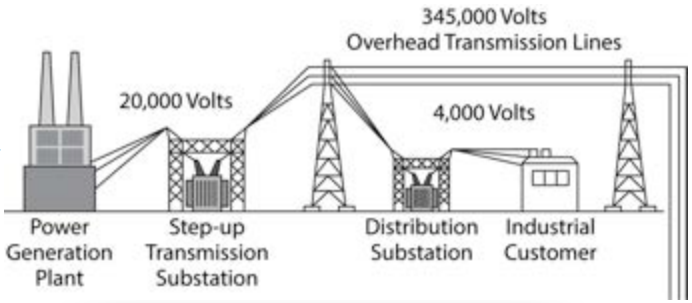
Central Station

Large Steam Turbines
Coal and Nuclear

Combustion Turbines
Natural Gas

Large Hydro Turbines
Dams and Pumped Storage

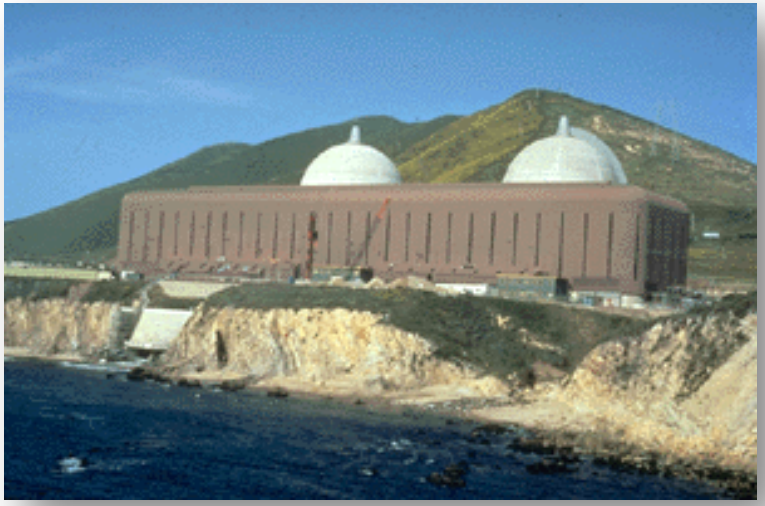
Electric Power System



Source: http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/index.html

Conventional Generation Sources

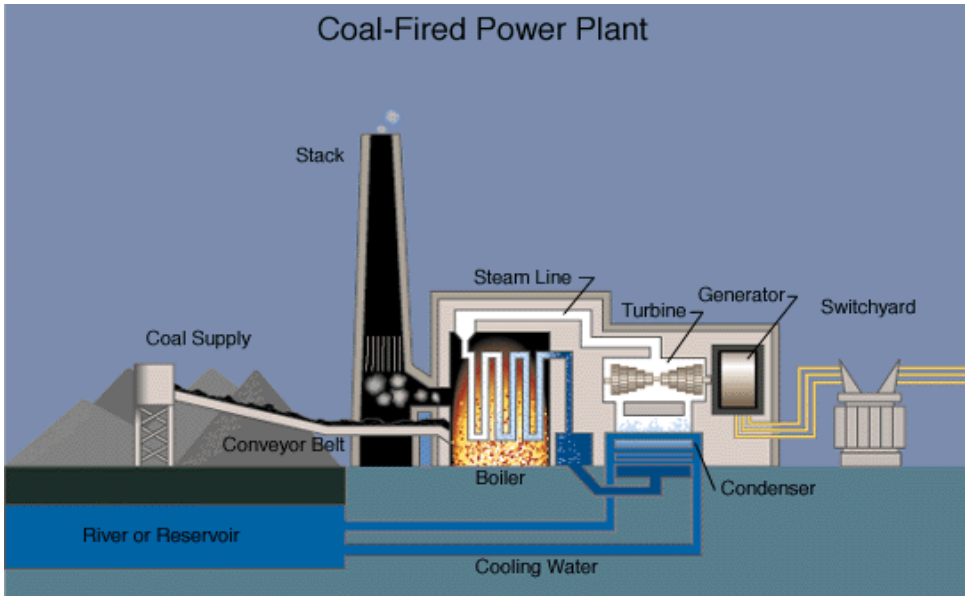
- Dispatchable
- Energy is inherently stored within source of fuel
- Use when needed
- Well understood and established technologies
- Highly reliable
- Easy to control



Source: http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/index.html

Conventional Power Generation Systems: Coal

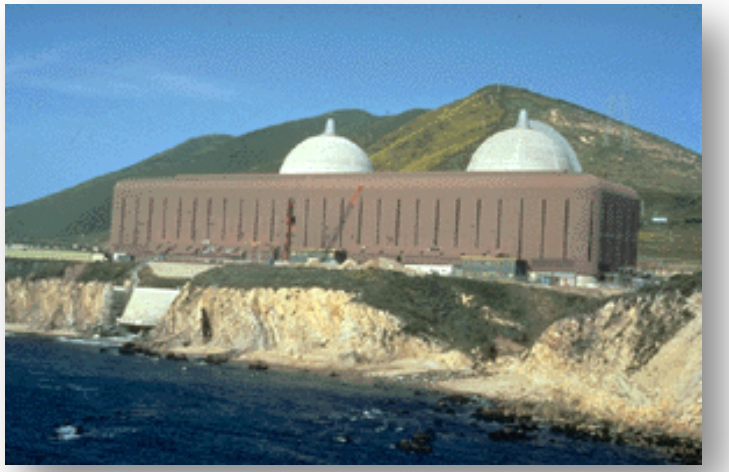
Source: http://www.tva.gov/power/coalart.htm

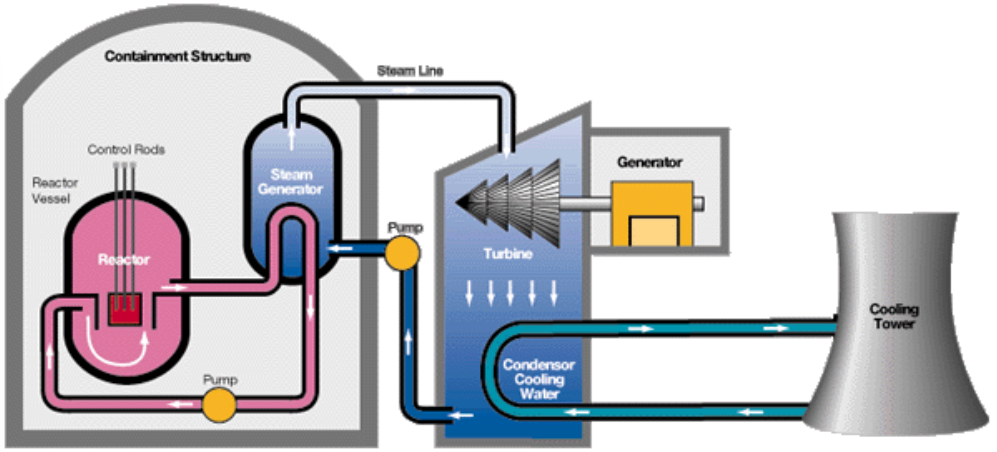


Characteristics:

- Low thermal efficiency (35%)
- Thermal pollution (condenser)
- Notable air pollution (Ash, CO_2, SO_2, NO_X)
- Long time required to start and stop
- Considered a base load unit: 2 MW/min ramp rates
- Large capital costs
- Current operating costs: between $17-$25/MWh

Conventional Power Generation Systems: Nuclear





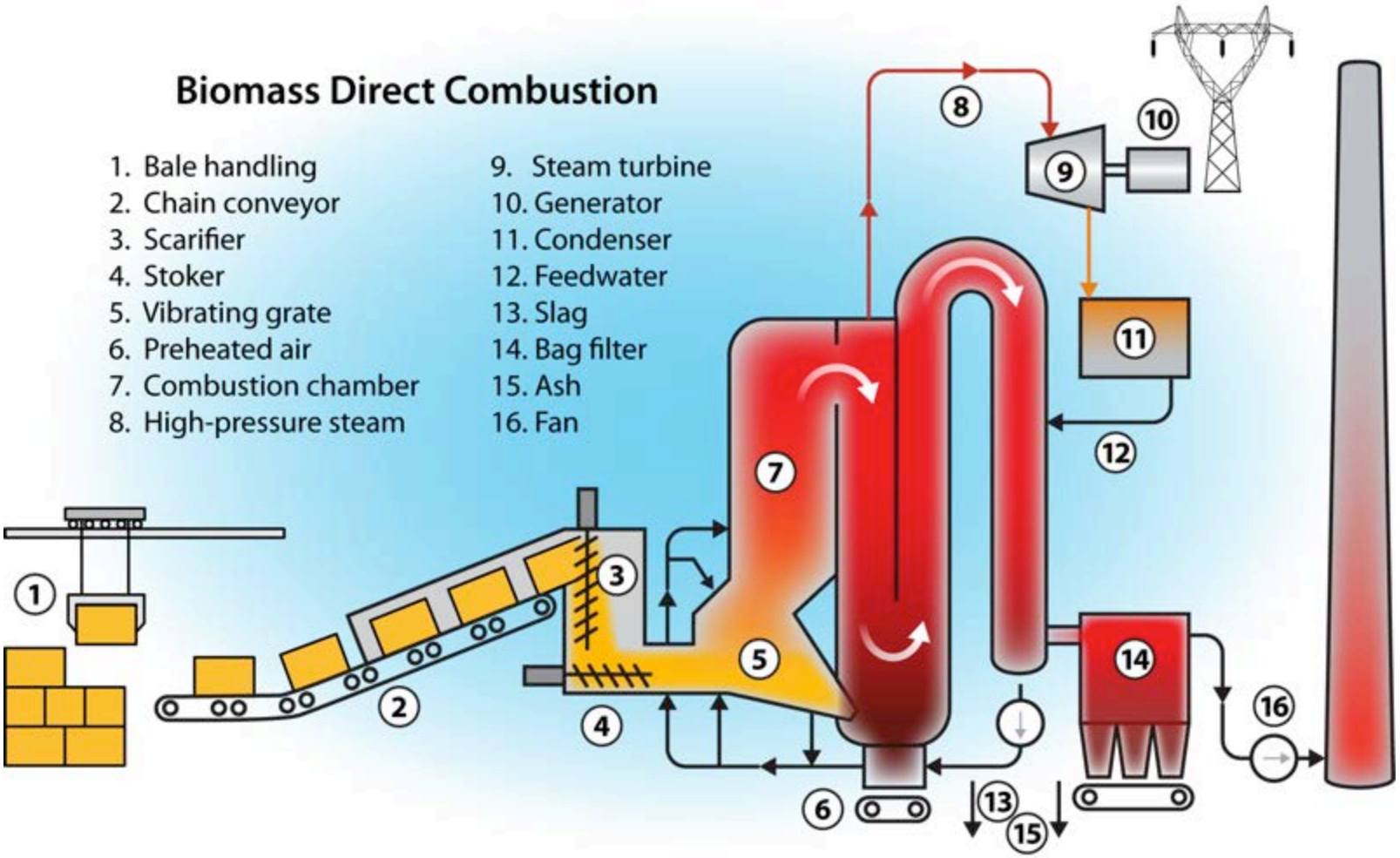
Source: Tennessee Valley Authority (TVA)

Characteristics:

- Low thermal efficiency (35%)
- No smoke stack (no emissions)
- Thermal pollution (condenser)
- Concerns about radioactive waste disposal
- Long time to start and stop
- These units are almost exclusively unavailable for dispatch, they generally remain fixed at the maximum output. Overseen by Nuclear Regulatory Council (NRC)
- Largest capital costs
- Current operating costs: between $8-$10/MWh

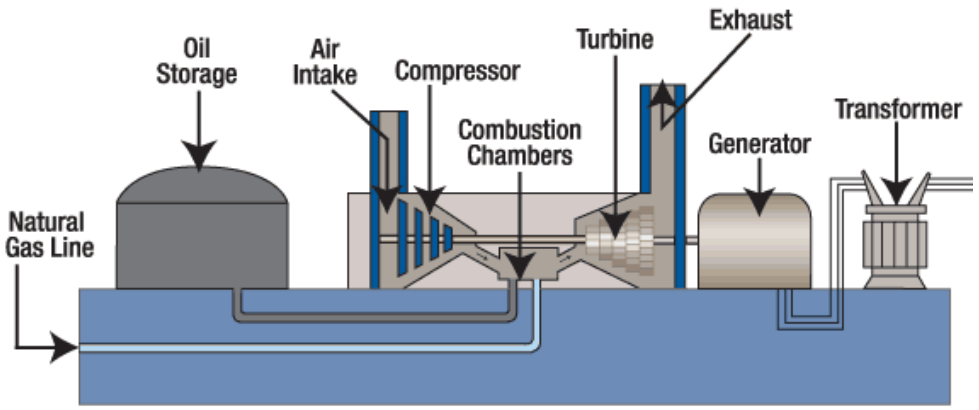
Source: http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/index.html

Conventional Power Generation: Steam Turbines (Biomass)



Combustion (Gas) Turbines – Simple Cycle

Source:
http://www.tva.gov/power/comb_cycle_video.htm

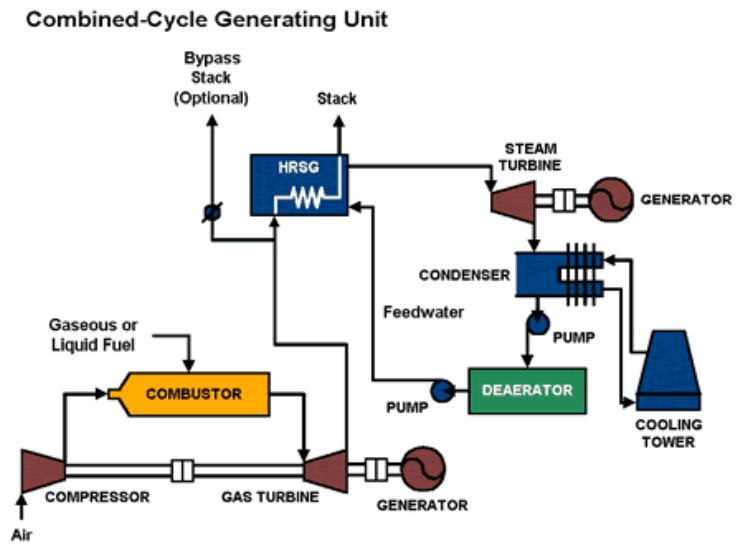


Reference: Tennessee Valley Authority (TVA)

Characteristics:

- These power plants burn fuel in a jet engine and use the exhaust gases to turn a turbine.
- Turbine draws in air, compresses it, mixes with fuel, and ignites
- Hot gases expand driving a generator
- Quick starting
- Load following or peaking unit: 10-12 MW/min ramp rates
- Relatively low capital costs
- Current operating costs: between $40-$50/MWh, depending on the cost of natural gas

Combustion (Gas) Turbines – Combined Cycle

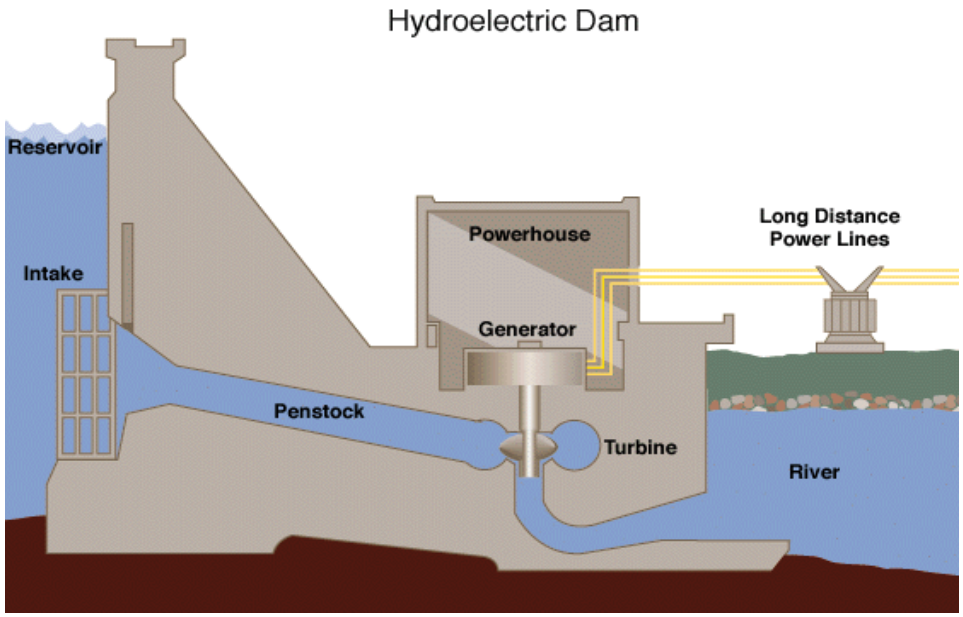


Reference: U.S. Department of Energy, Energy Efficiency and Renewable Energy

Characteristics:

- Turbine draws in air, compresses it, mixes with fuel and ignites
- Hot gases expand driving a generator
- Heat Recovery Steam Generator (HRSG): Exhaust heat is routed to a boiler, and the steam is used to produce additional power
- Because of the higher efficiency, these units are the lowest cost natural gas-fueled generators
- Current operating costs: between $28-$35/MWh, depending on the cost of natural gas

Conventional Power Generation Systems: Hydroelectric



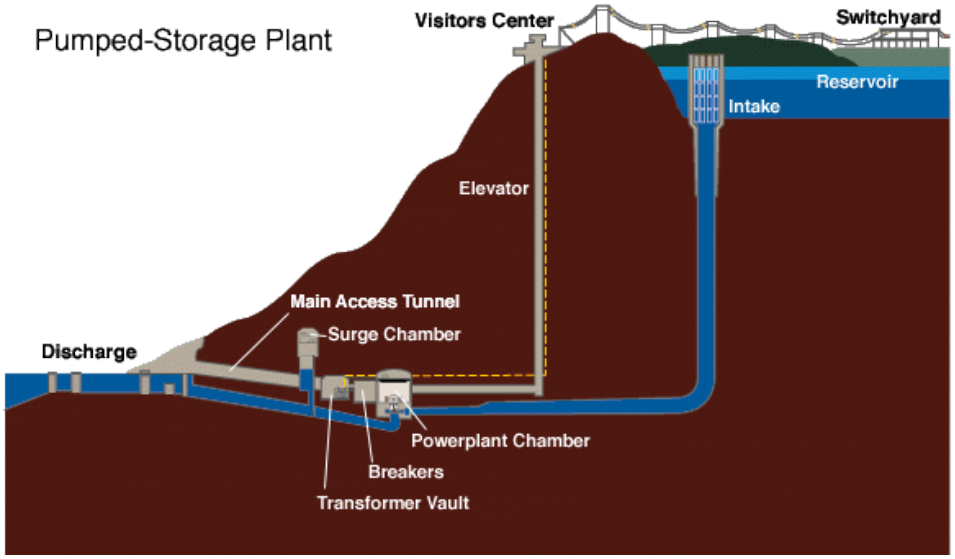
Reference: Tennessee Valley Authority (TVA)

Characteristics:

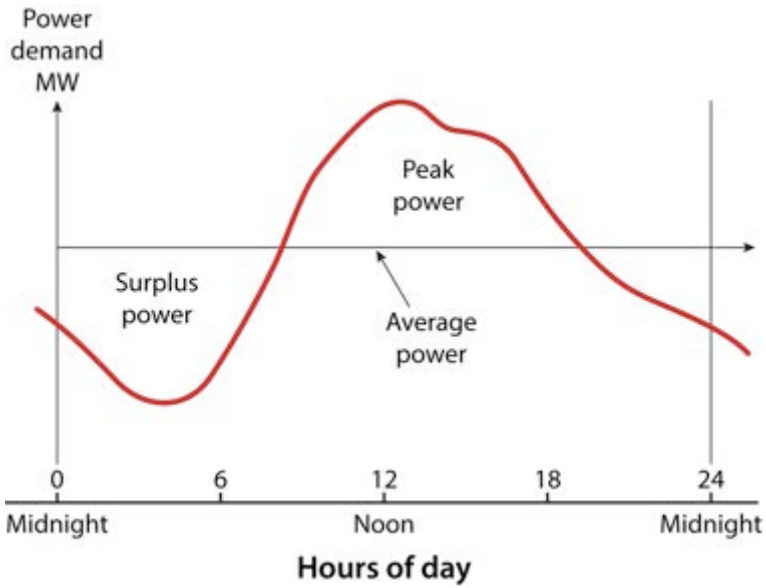
- High efficiency (85-90%)
- Considered a renewable energy source
- Very short start times and easy to control
- Environmental concerns (water flows and siltation)
- Very inexpensive source of power

Source: http://www.tva.gov/power/hydro.htm

Conventional Generation: Hydroelectric Pumped Storage



Reference: Tennessee Valley Authority (TVA)



Characteristics:

- Uses electricity during low demand times to pump water from the low-elevation reservoir to the high-elevation reservoir.
- During peak power demands the water flows back down acting like a conventional hydroelectric facility.
- The difference in pricing during the day and night makes this type of unit very lucrative.

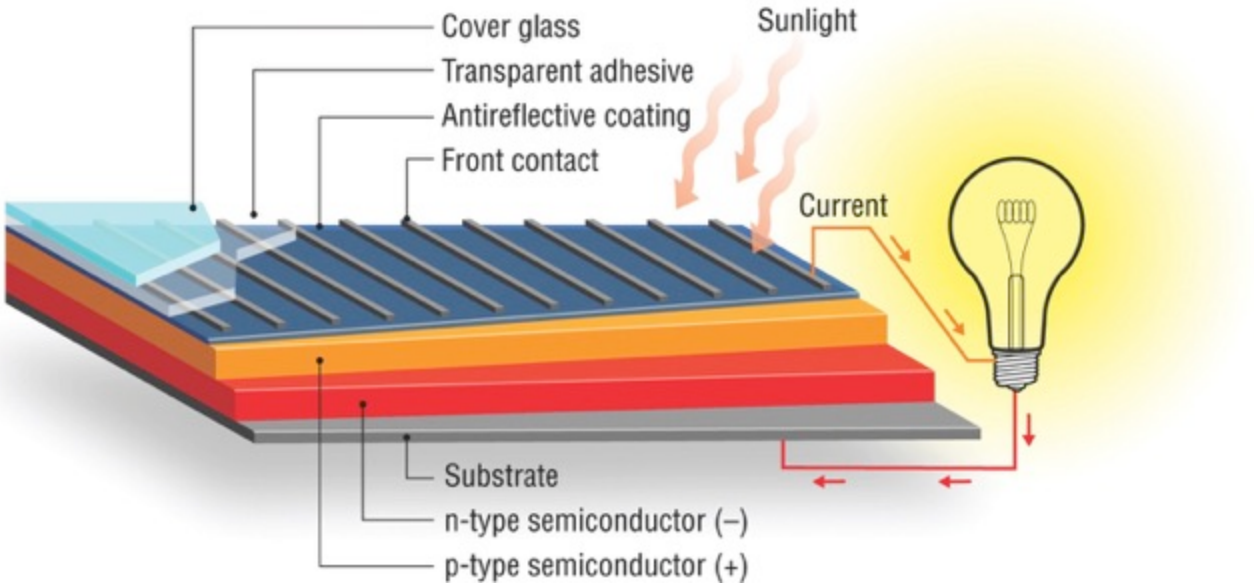
Renewable Power Generation Systems

Source:
http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/index.html

NREL/TP-6A20-51137. April 2012

- Non-Dispatchable
- Considered to be unconventional generation sources
- Characterized by variability and uncertainty
- Energy source must be used when available
- More difficult to control
- More difficult to schedule
- Use it or lose it!

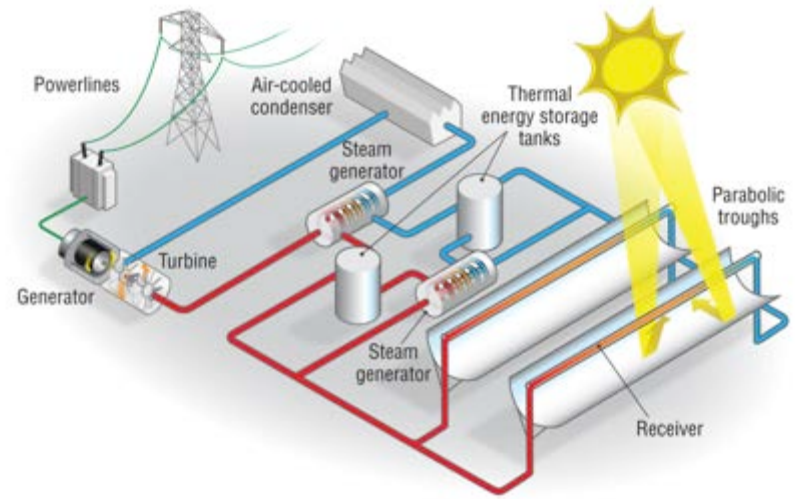
Renewable Power Generation: Solar Photovoltaic

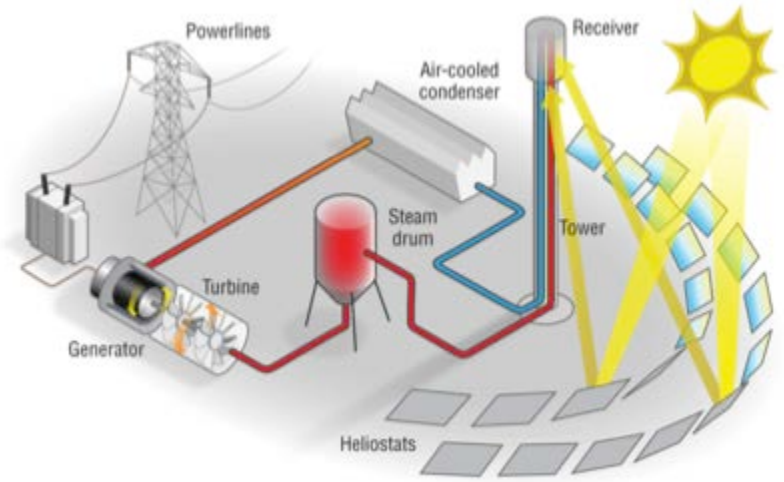


Characteristics:

- Low conversion efficiency (15-25%)
- Directly converts solar radiation into electricity
- Produces direct current, converted to alternating current by inverter
- Can generate electricity from direct and diffuse solar radiation (sunny and cloudy conditions)
- High capital costs and space requirements
- Low operating costs (few moving parts, no fuel cost)

Renewable Power Generation: Concentrating Solar Power





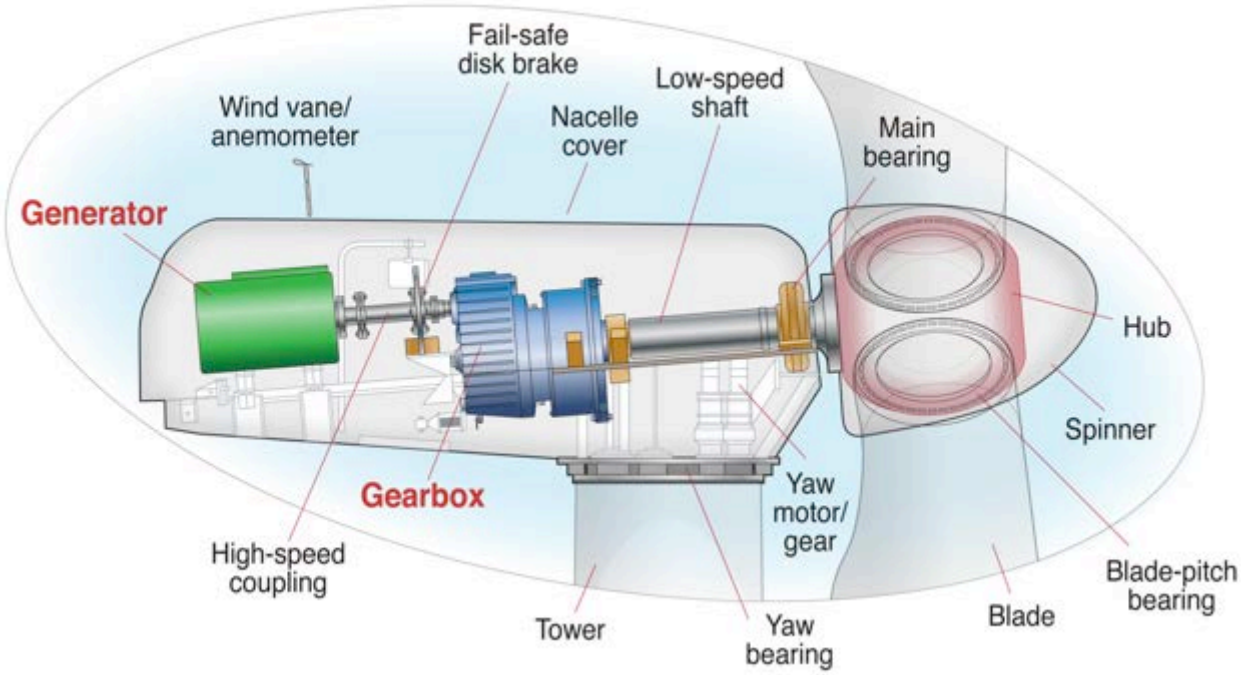
Characteristics:

- Converts solar energy to thermal energy (steam), which drives turbine to generate electricity
- Requires direct solar radiation to generate heat
- May heat water directly or use a working fluid (e.g. oil) to collect heat and later transfer to water to create steam
- Can store thermal energy in molten salt or other media, allows generation of electricity into evening/night
- Can be coupled with conventional fuels to generated steam/electricity 24/7
- High capital cost

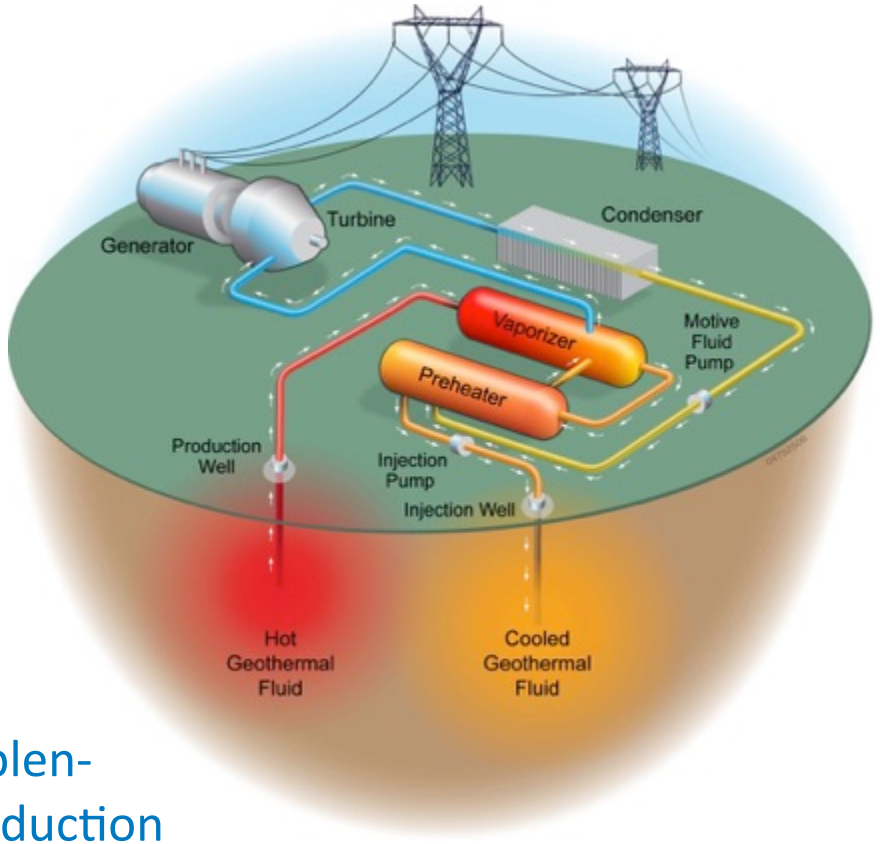
Renewable Power Generation Systems: Wind

Characteristics

- Converts kinetic energy of air into electricity via gearbox and generator
- Generation depends entirely on wind availability
- Turbines have a “cut-in” speed (minimum start-up speed) and a “cut-out” speed (maximum safe operation speed)
- Wide variation in rated capacity of machines
- Energy generated is highly site-dependent
- High capital costs
- Low operating costs



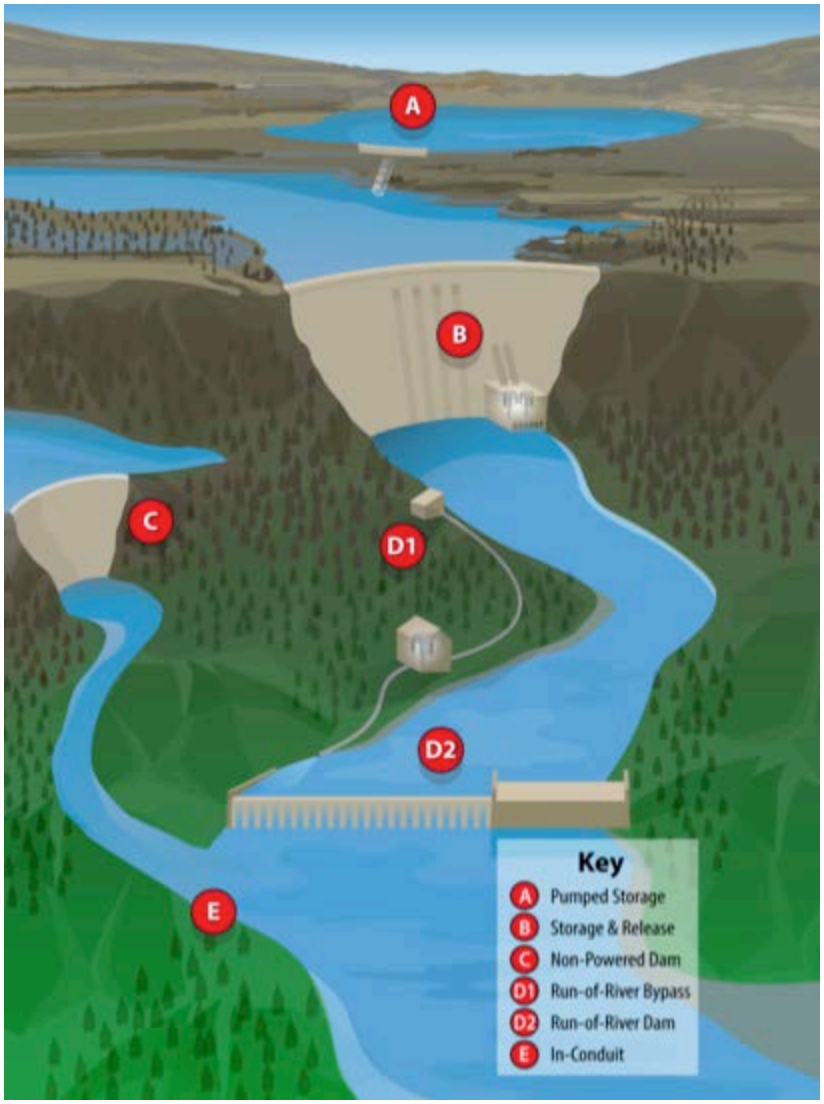
Renewable Power Generation Systems: Geothermal



Characteristics

- Facilities use energy from geologic sources to produce steam, drive turbine to produce electricity
- Can produce energy on demand (operates as baseload in many locations, e.g. California)
- Energy generation highly location-dependent
- Underground resources may require replen-ishment of water to continue steam production
- Areas producing geothermal energy can be exhausted over time
- High capital costs
- Moderate operating costs (disposal of produced water, reinjection, monitoring

Renewable Power Generation Systems: Small Hydroelectric



Characteristics:

- Smaller scale than conventional hydroelectric
- May remove a portion of flow from a river or canal to generate power
- Run-of-river system passes some portion of river flow through turbine, returns to main river downstream
- Lack of dam means no storage, potential lower environmental impact but less dispatchable
- Highly site-dependent
- High capital cost
- Moderate operational cost

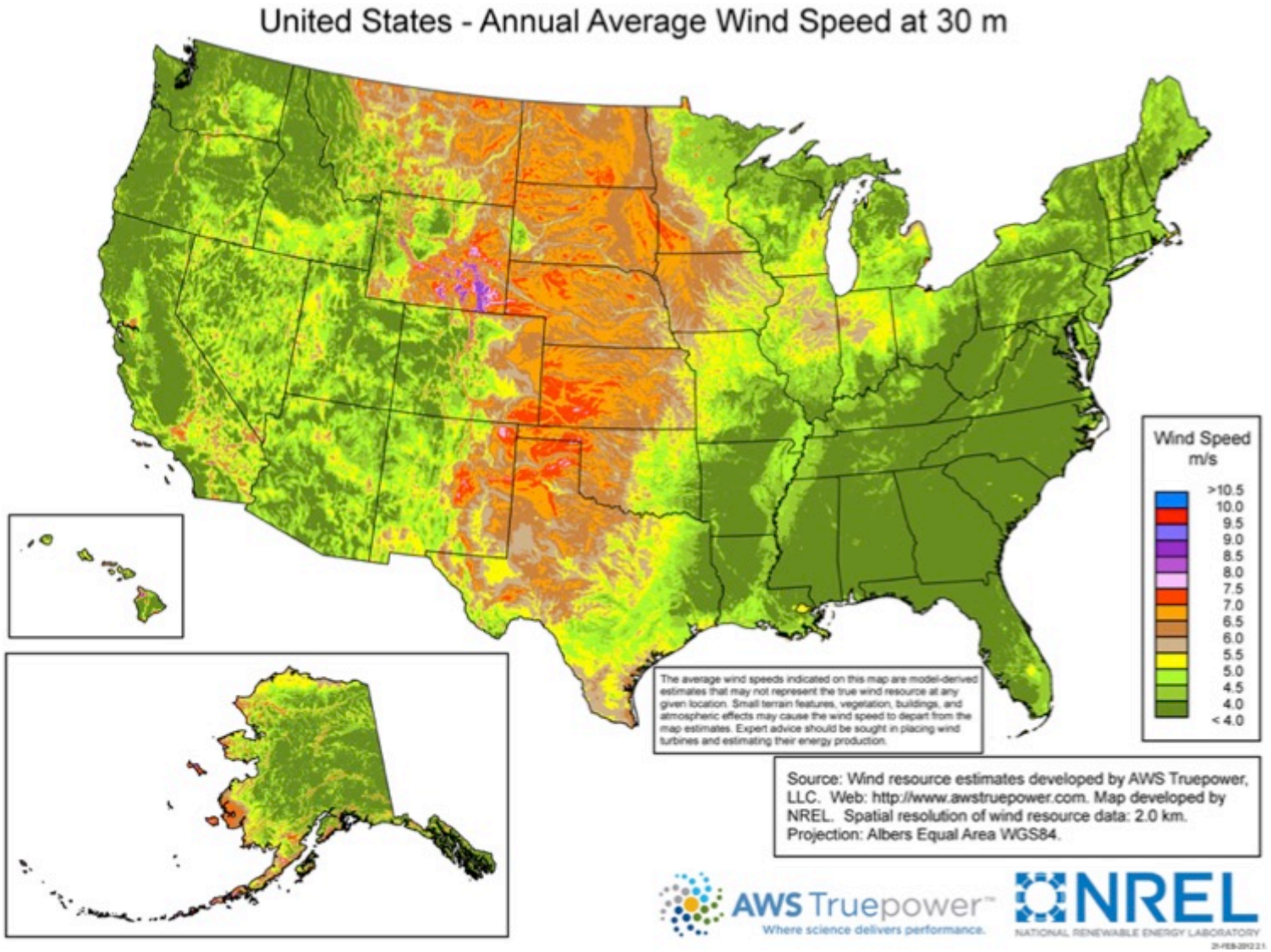
Wind

NREL PIX 21873

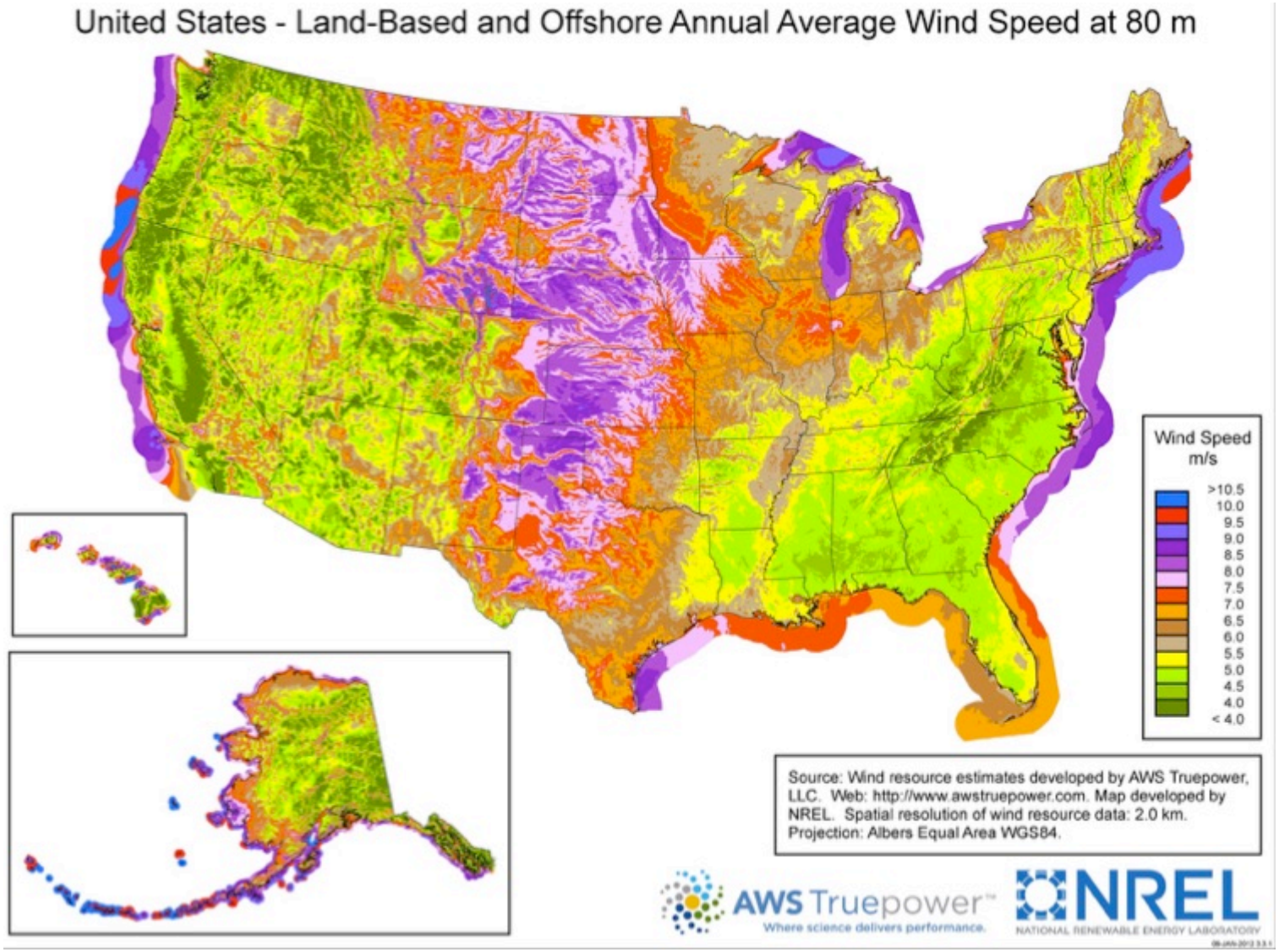
Distributed Wind

Photo from: *N. Blitterswyk, "A Bipartisan Group of Senators Is Pushing For Distributed Wind – Here's Why It Matters". Cleantechnica.com, 29 Dec 2014.*

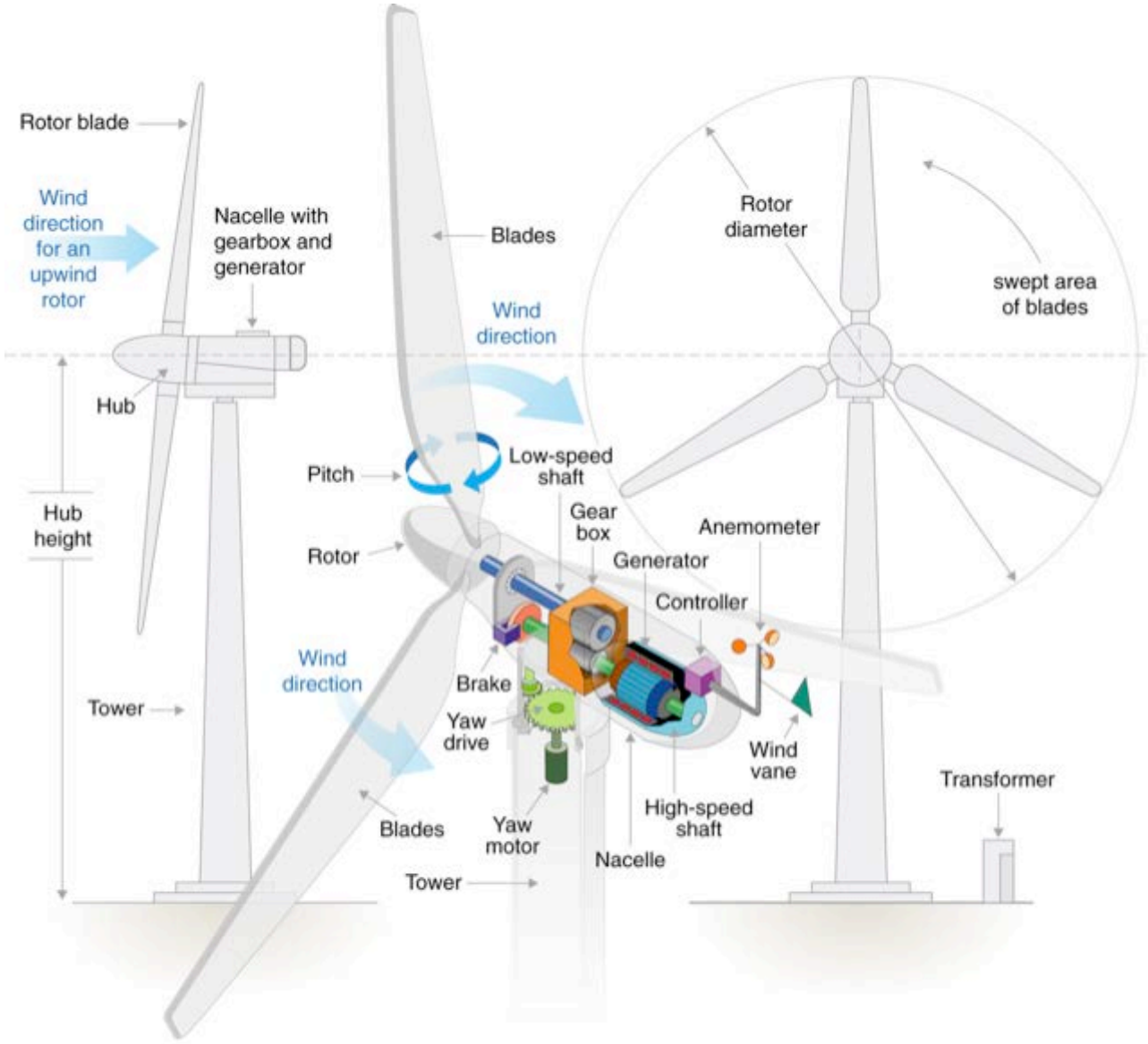
Wind Resource Map – 30 m



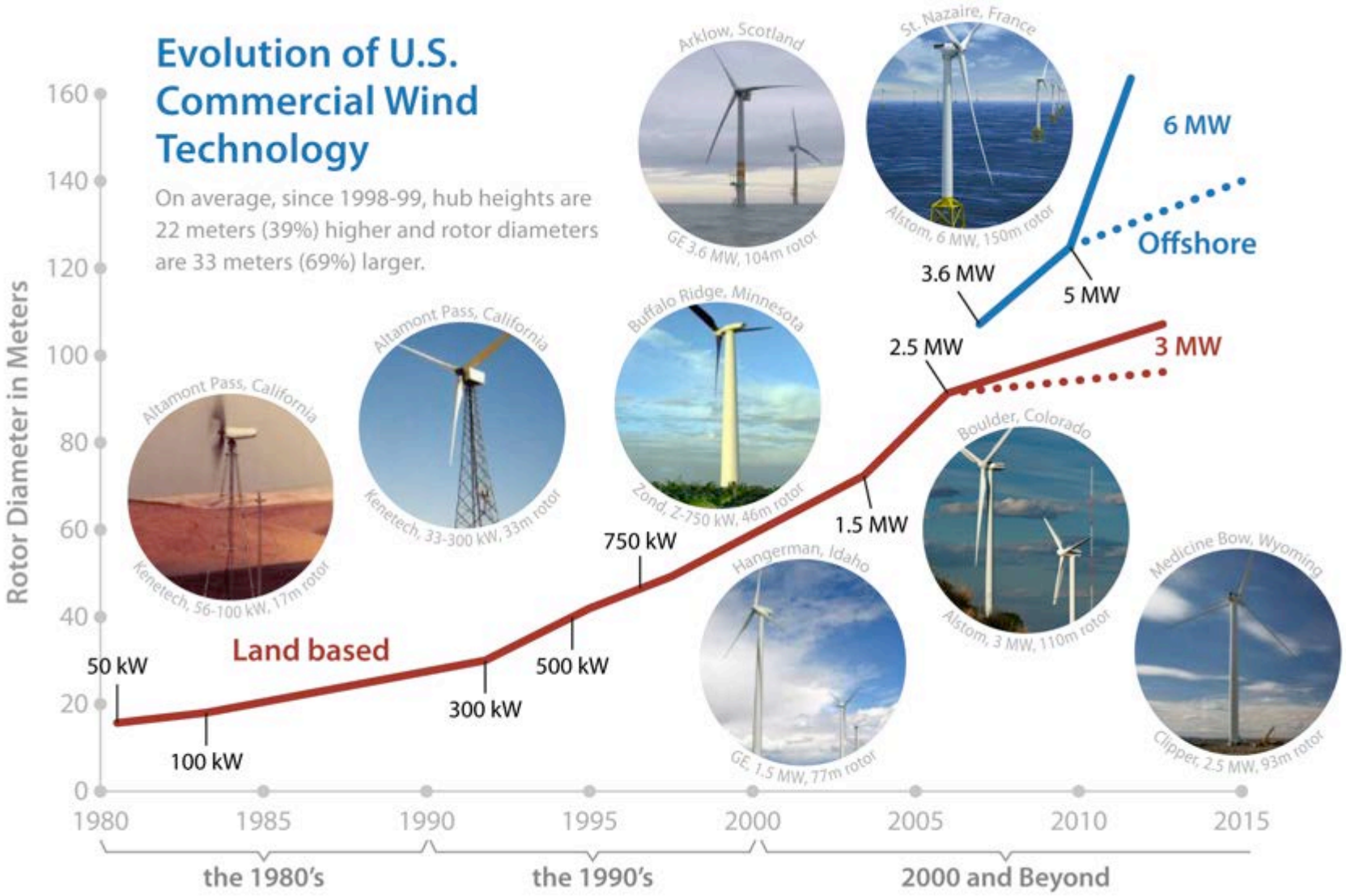
Wind Resource Map – 80 m



Wind Turbine Components



Average Hub Heights and Rotor Diameters Over Time



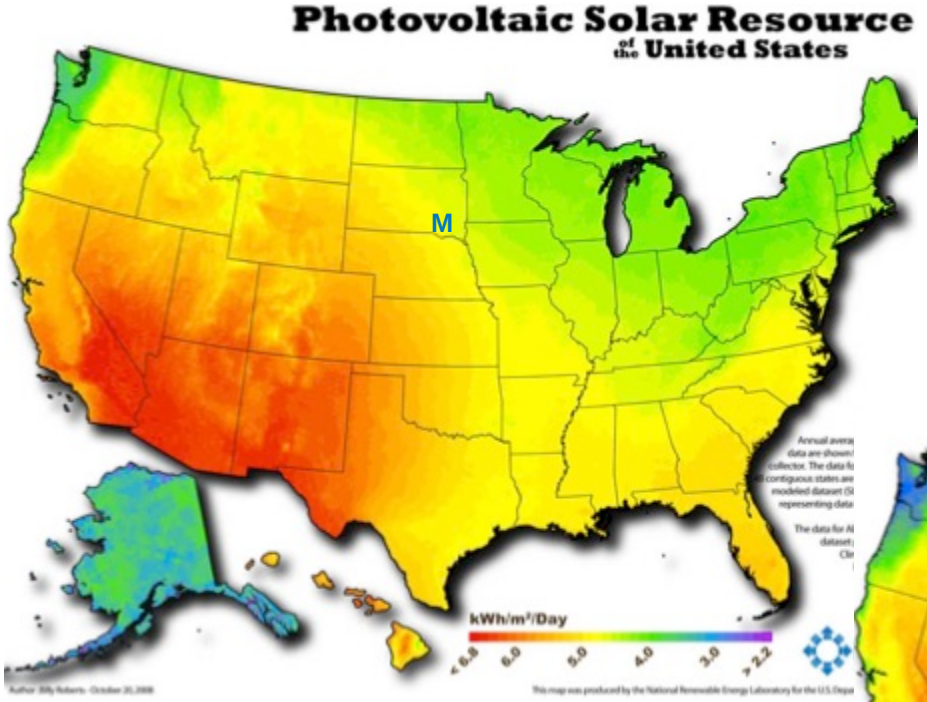
Solar Energy Technologies

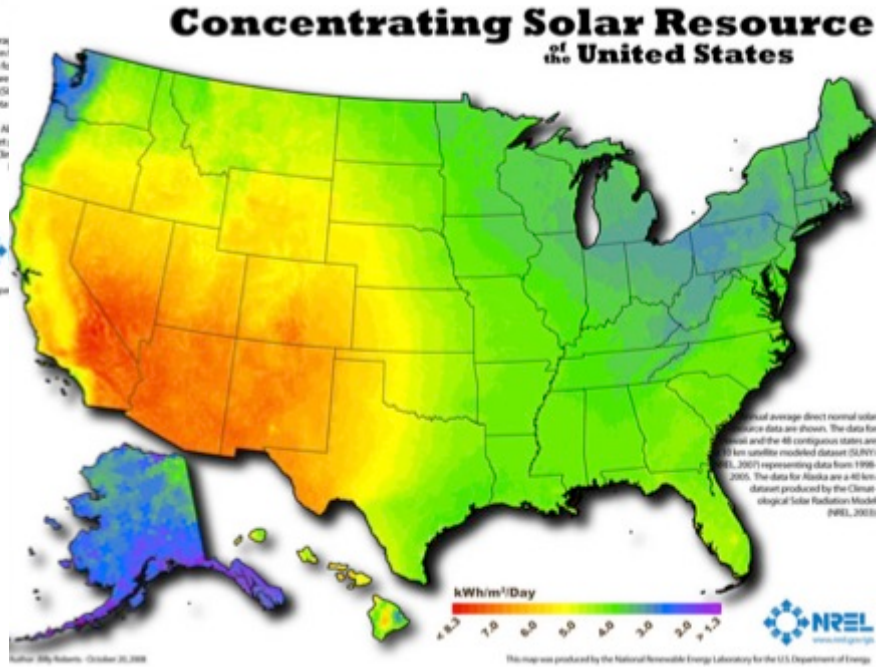
NREL PIX 15563

Solar Energy Technologies

Photovoltaic	Concentrated Solar Power	Solar Heating	Solar Lighting
			
PV systems use semiconductors to convert sunlight directly to energy.	CSP systems focus the sun's heat onto a generator to produce electricity.	Solar collectors absorb the sun's energy to provide low temperature space or water heating.	Passage for natural interior lighting or piping light indoors using fiber optics.
Energy Conversion			
Light → Electricity	Heat → Electricity	Heat → Heat	Light → Light
Conversion Type			
Direct	Indirect	Direct	None

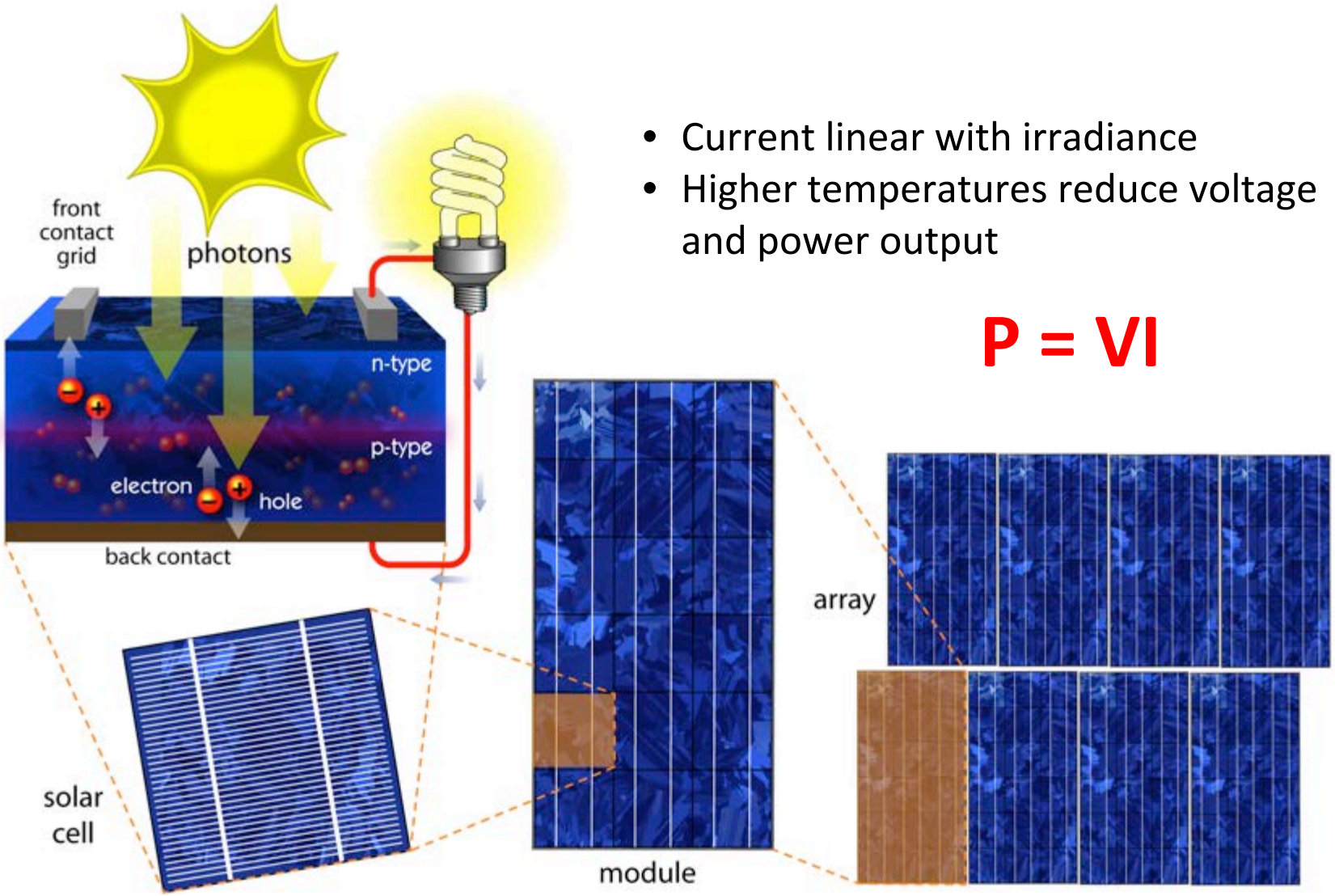
United States - Solar Resources





Type of system determined by local solar resource

PV Basics

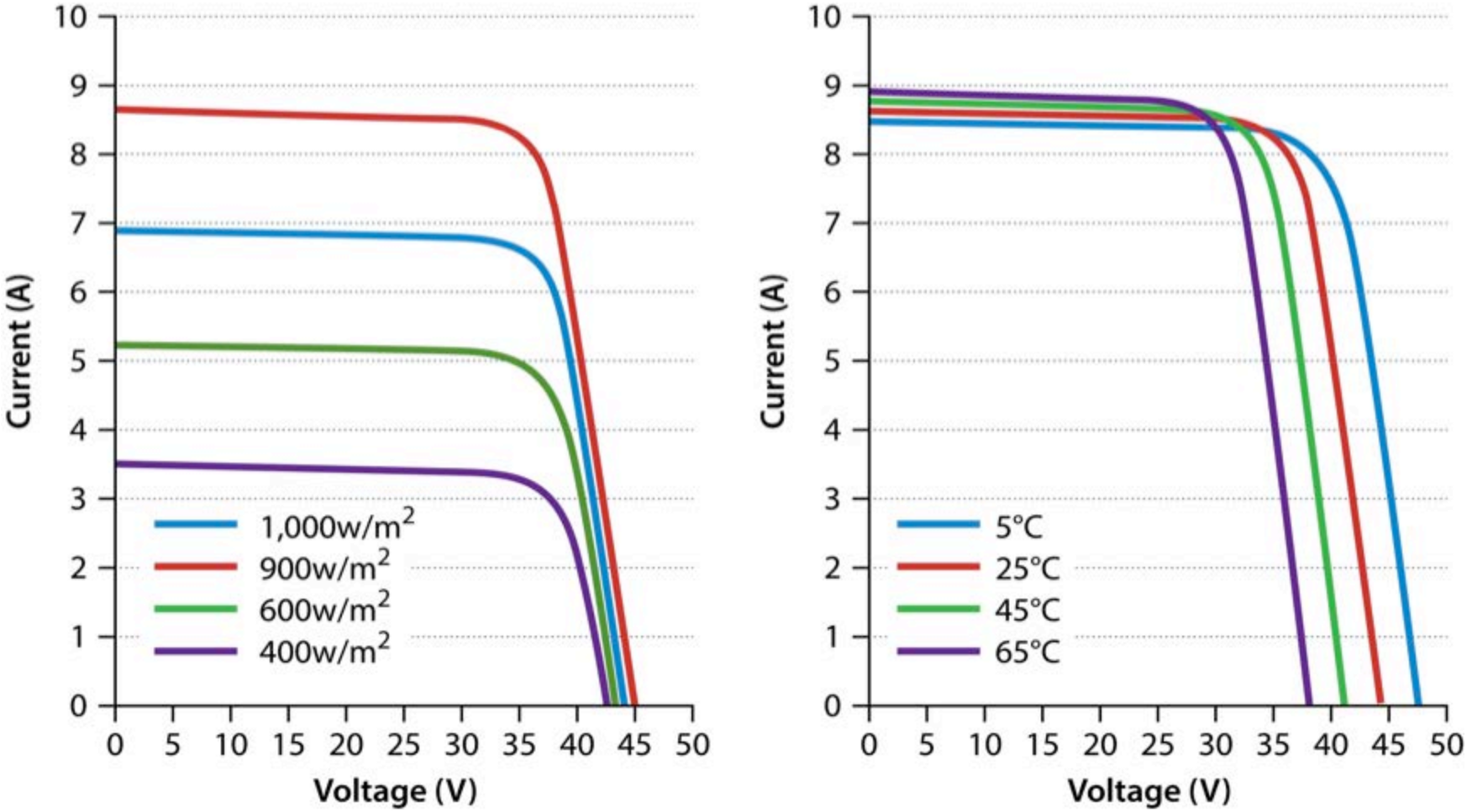


- Current linear with irradiance
- Higher temperatures reduce voltage and power output

P = VI

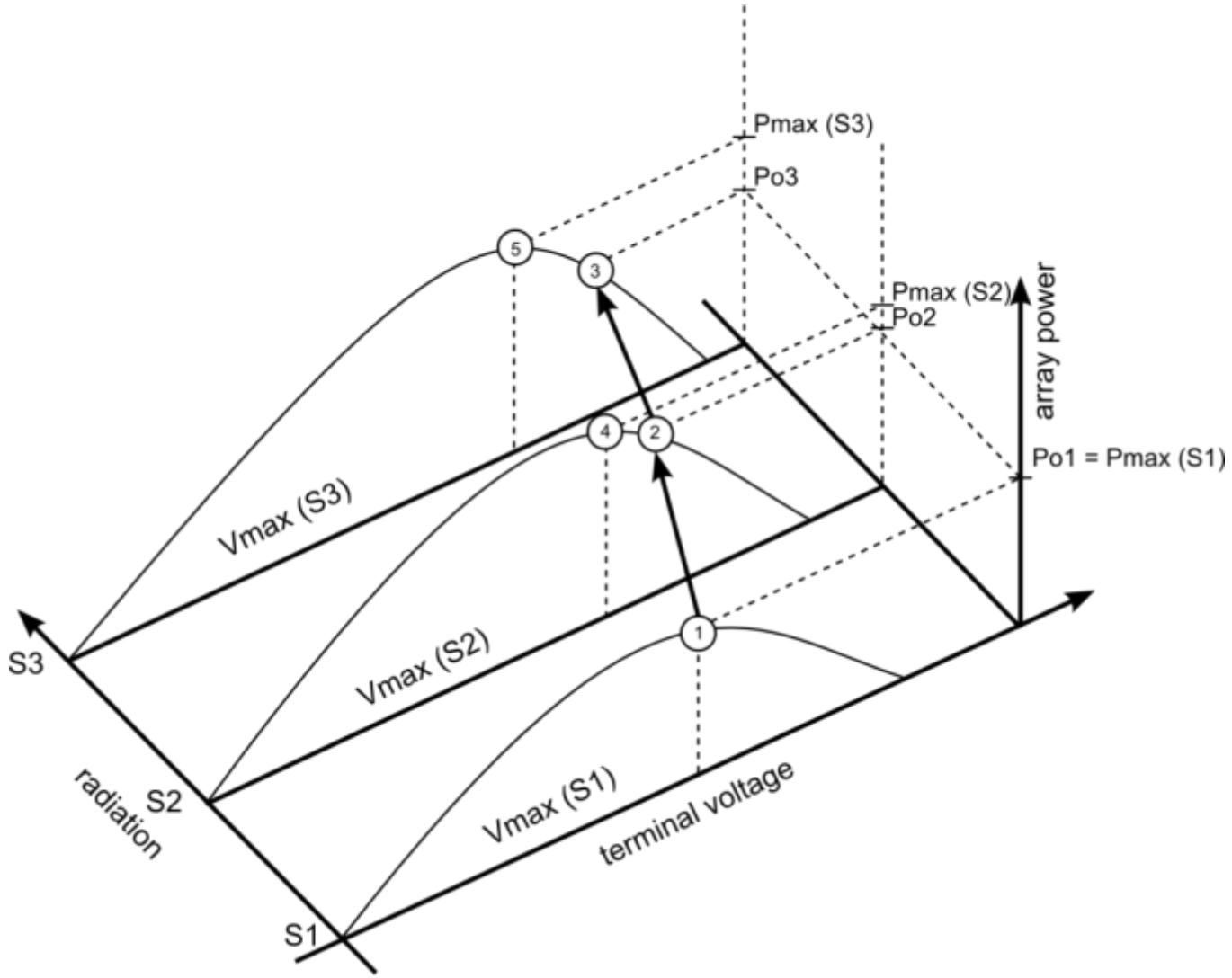
PV Basics

Irradiance and Temperature Effects on PV Output (I-V Curves)



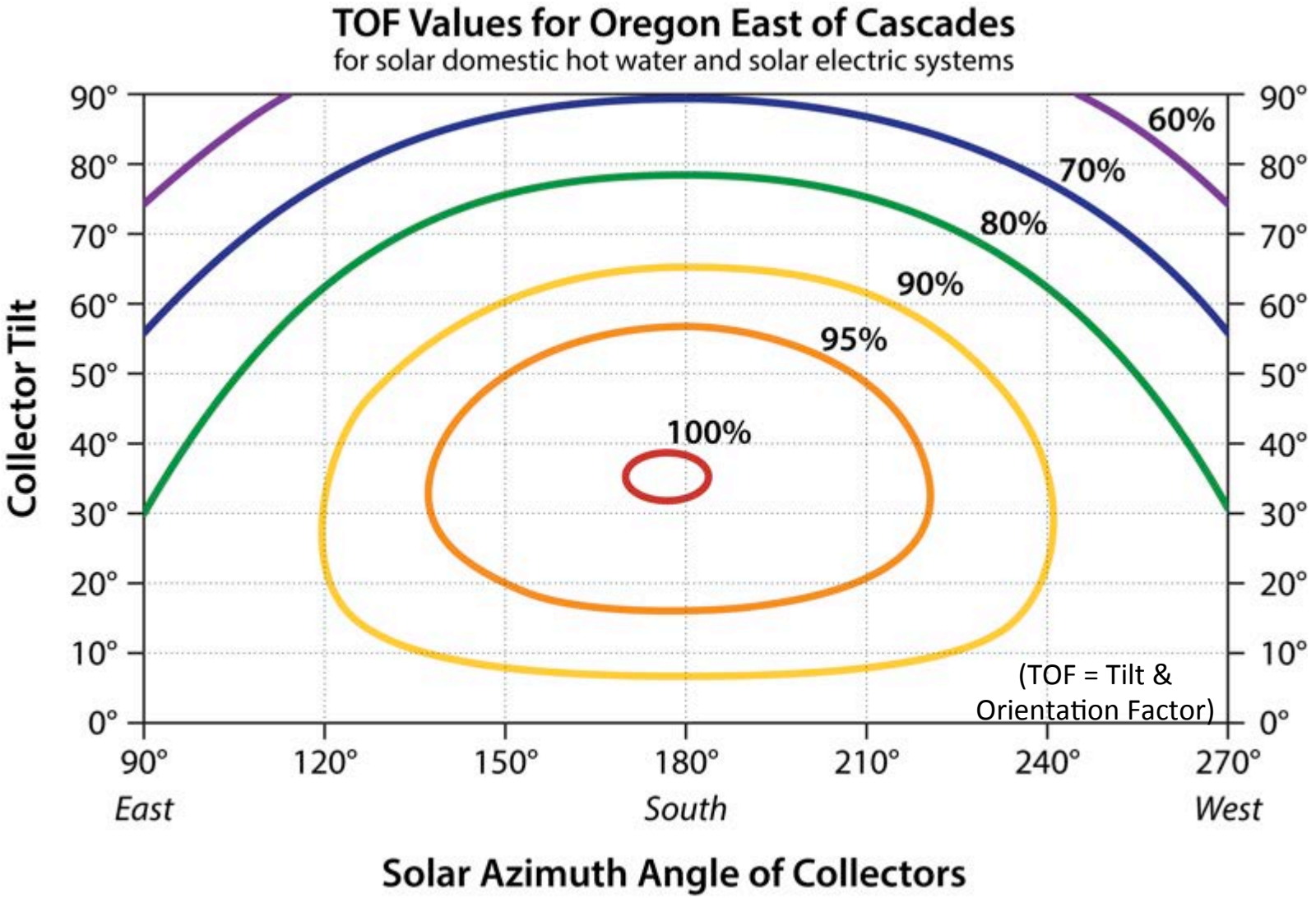
Source: Canadian Solar MaxPower CS6X Product Data Sheet

Solar Resource Over Time



Source: Advanced Energy, *SEGIS Technology Demonstration: Solutions for High Penetration Solar PV*

Array Tilt and Orientation



Source: www.oregon.gov/ENERGY/RENEW/Solar/docs/SunChart.pdf

Tracking Configurations

Fixed-Tilt Array

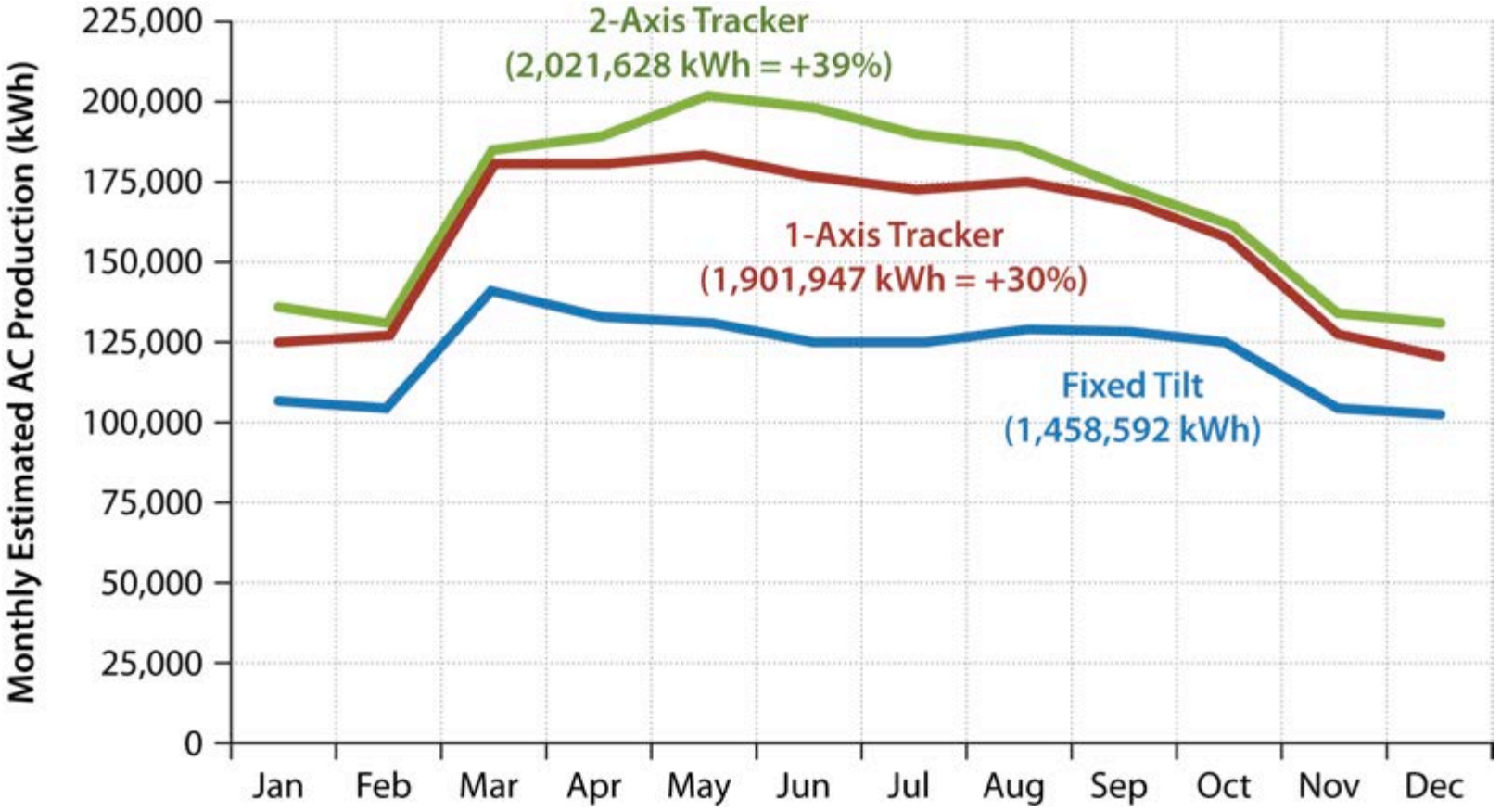
Horizontal 1-Axis Tracking

Tilted 1-Axis Tracking

2-Axis Tracking CPV

Tracking Systems vs. Monthly AC Energy Production

1-MW Array in Boulder, Colorado
Fixed Tilt, 1-Axis and 2-Axis Tracking

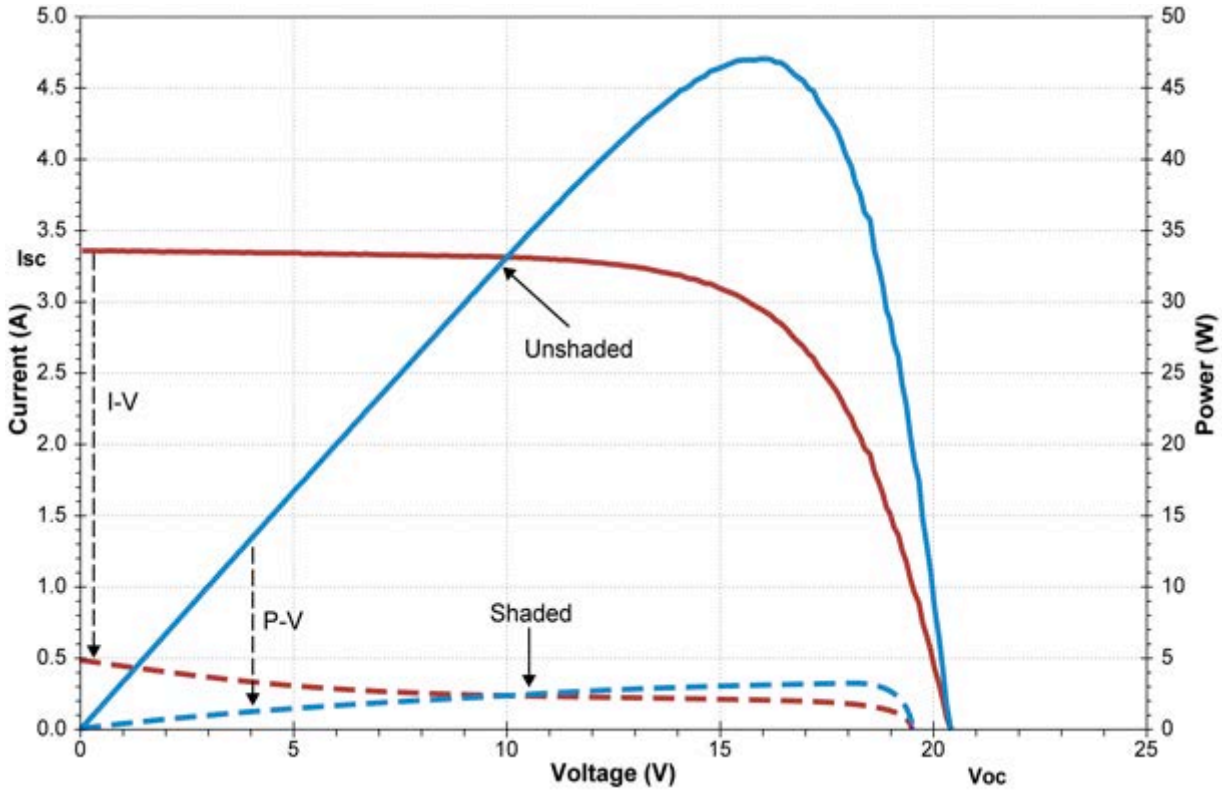


Source: P. McNutt, NREL. Modeled using PVWatts: http://www.nrel.gov/rredc/pvwatts/site_specific.html

PV Module Shading

Minor PV module shading can reduce output dramatically

Source: Peter McNutt, NREL



I-V and P-V curves of an unshaded and shaded crystalline-silicon module - shading just **7%** of the module area yields a **93% drop** in its output power!

PV Inverter Overview

- Converts DC from PV Modules to AC into Utility Grid
- Implements Maximum Power Point Tracking
- Provides system monitoring
- Implements grid interactive features