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Teaching Materials - Renewable Energy Presentation Slides

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Introduction to Renewable Energy

Lecture 1: Introduction and Overview of Renewable Energy Resources (RESs) (1/2)

IREEDER

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Section Outline

In this section, an overview of energy use, from fossil fuels to renewable energy is presented. Renewable energy types are introduced and a description of their characteristics is given.

Section 1

Introduction to Renewable Energy

This week's topics…

- Overview of energy use
- Fossil fuels
- Solar Energy
- Wind Energy
- Bioenergy

Overview of Energy Use

- Energy demands increase as population rises
- Residential, commercial, industrial energy needs increase
- Fossil fuels, nuclear fuel, renewable resources are used for energy production
- Continuous increase in the use of fossil fuels

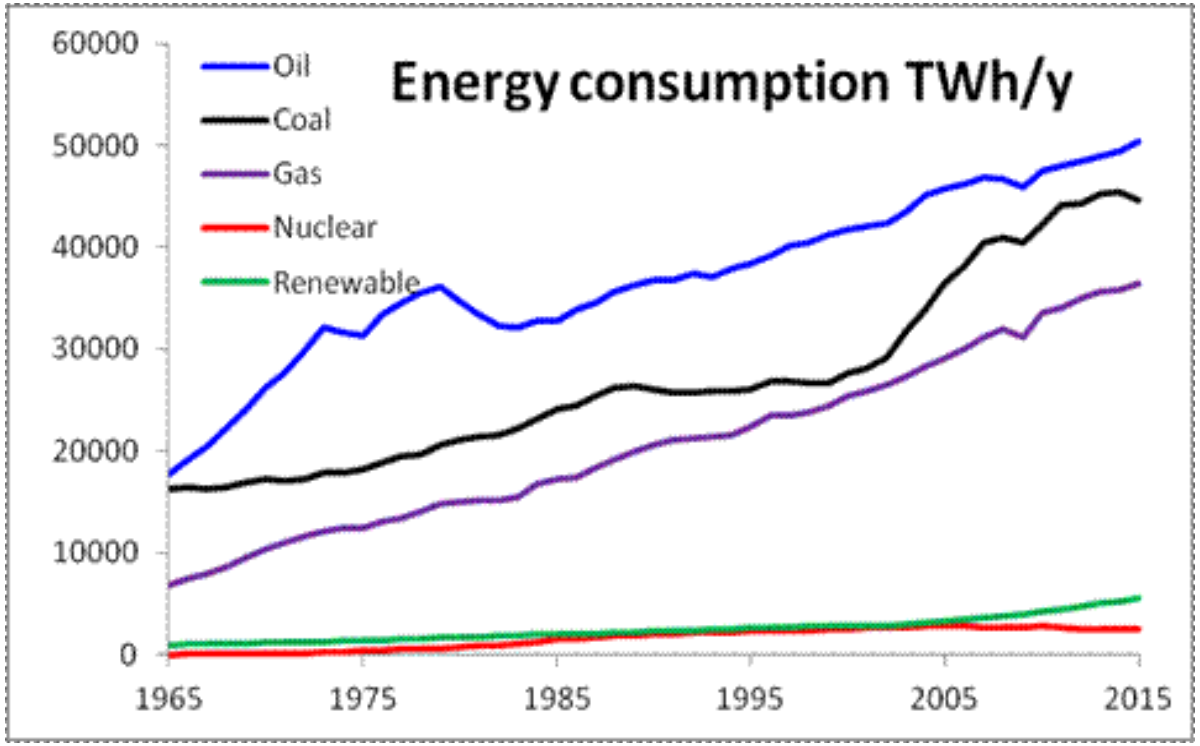


Figure 1-1: World's energy consumption based on data from 2015.

Overview of Energy Use

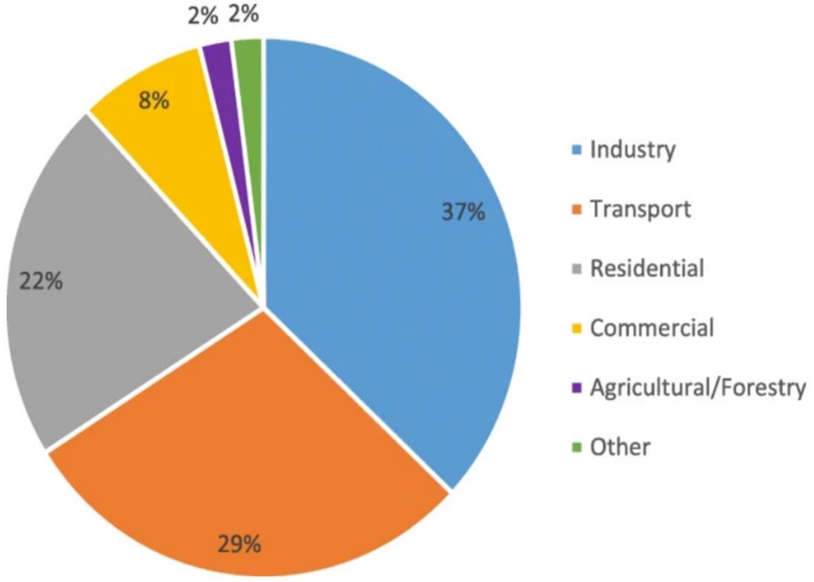
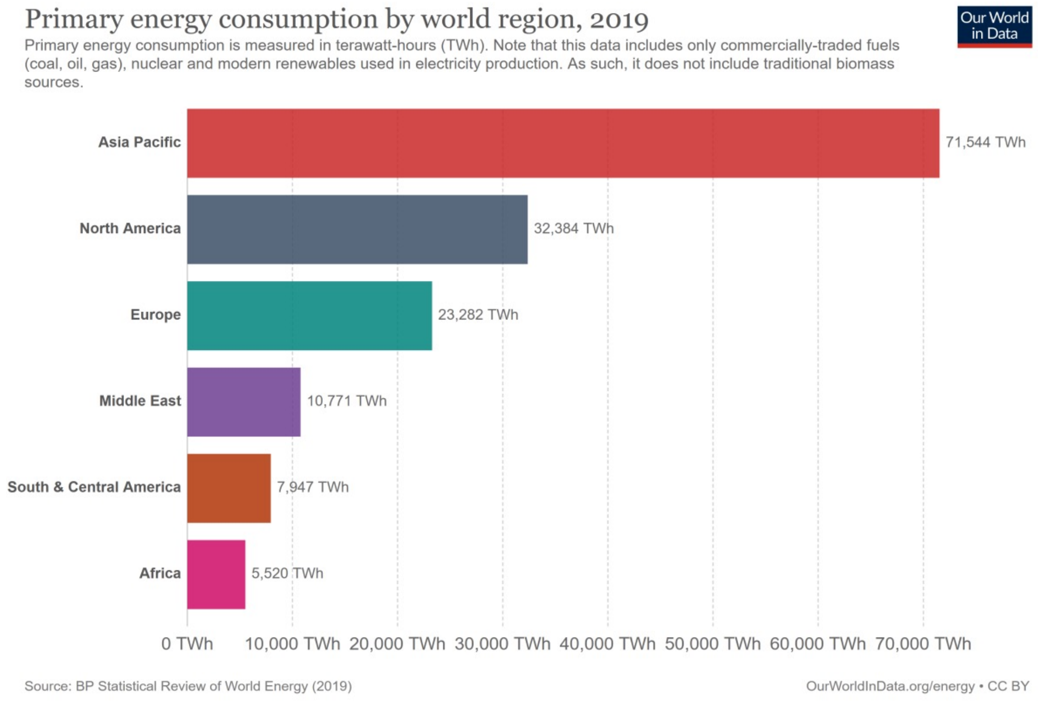


Figure 1-2: Total energy consumption by sector for 2015 and 2016.

- Industrial and transport, highest energy consumption
- Asia Pacific, North America, Europe the highest consumers
- Africa’s consumption the lowest globally
- 2018: USA consumption 13.1 Mwh/capita,

  Bangladesh 0.5 MWh/capita


Primary energy consumption by world region, 2019

Primary energy consumption is measured in terawatt-hours (TWh). Note that this data includes only commercially-traded fuels (coal, oil, gas), nuclear and modern renewables used in electricity production. As such, it does not include traditional biomass sources.

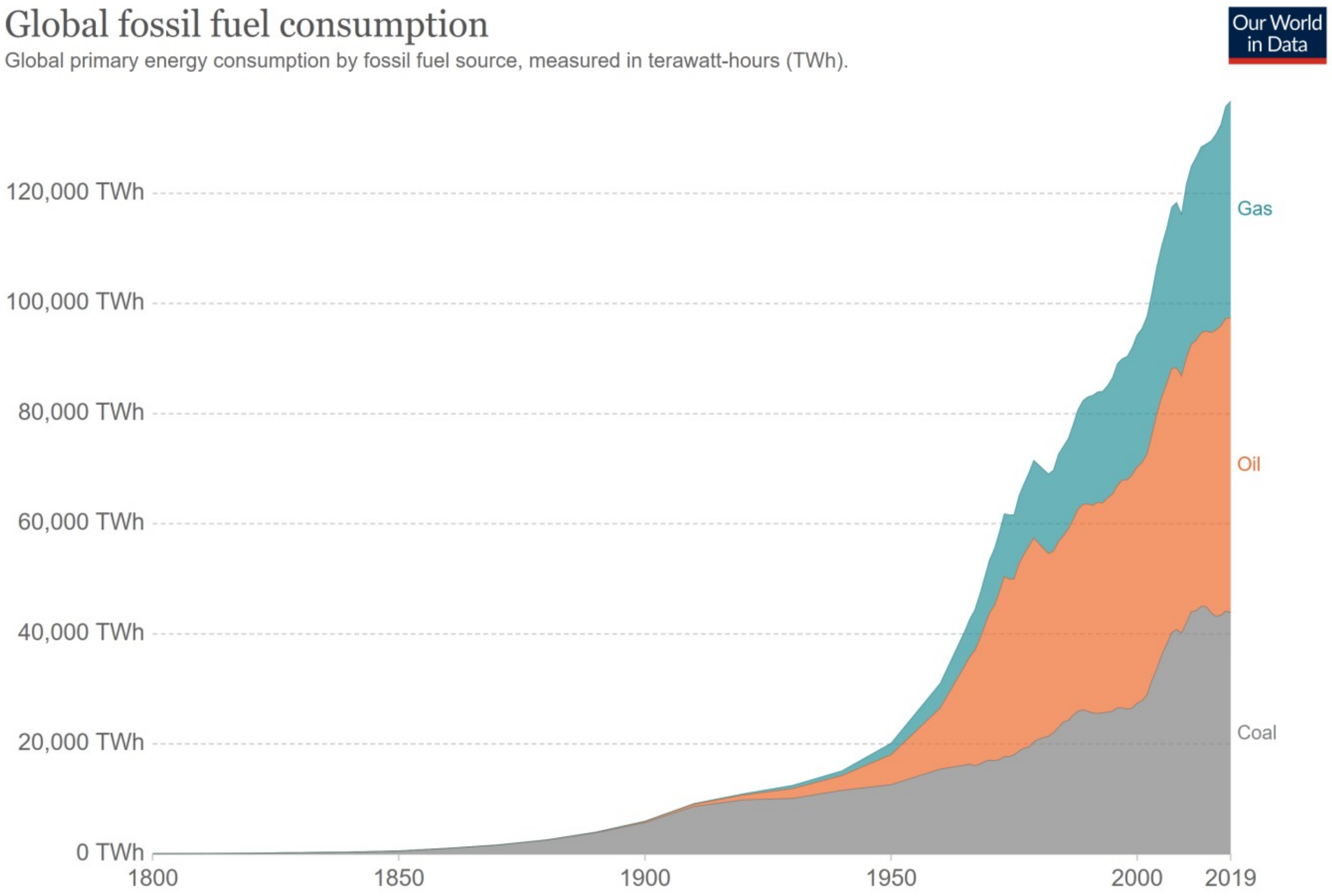
Source: BP Statistical Review of World Energy (2019)

OurWorldInData.org/energy • CC BY

Figure 1-3: Primary energy consumption by region in 2019.

Fossil fuels

- Fossils fuels are formed from buried organic material
- It takes millions of years for formation
- Carbon rich, energy is released from their combustion
- Non-renewable resources



Source: Vaclav Smil (2017). Energy Transitions: Global and National Perspective & BP Statistical Review of World Energy OurWorldInData.org/fossil-fuels/ • CC BY

Figure 1-4: World's fossil fuel consumption for the period 1800-2019.

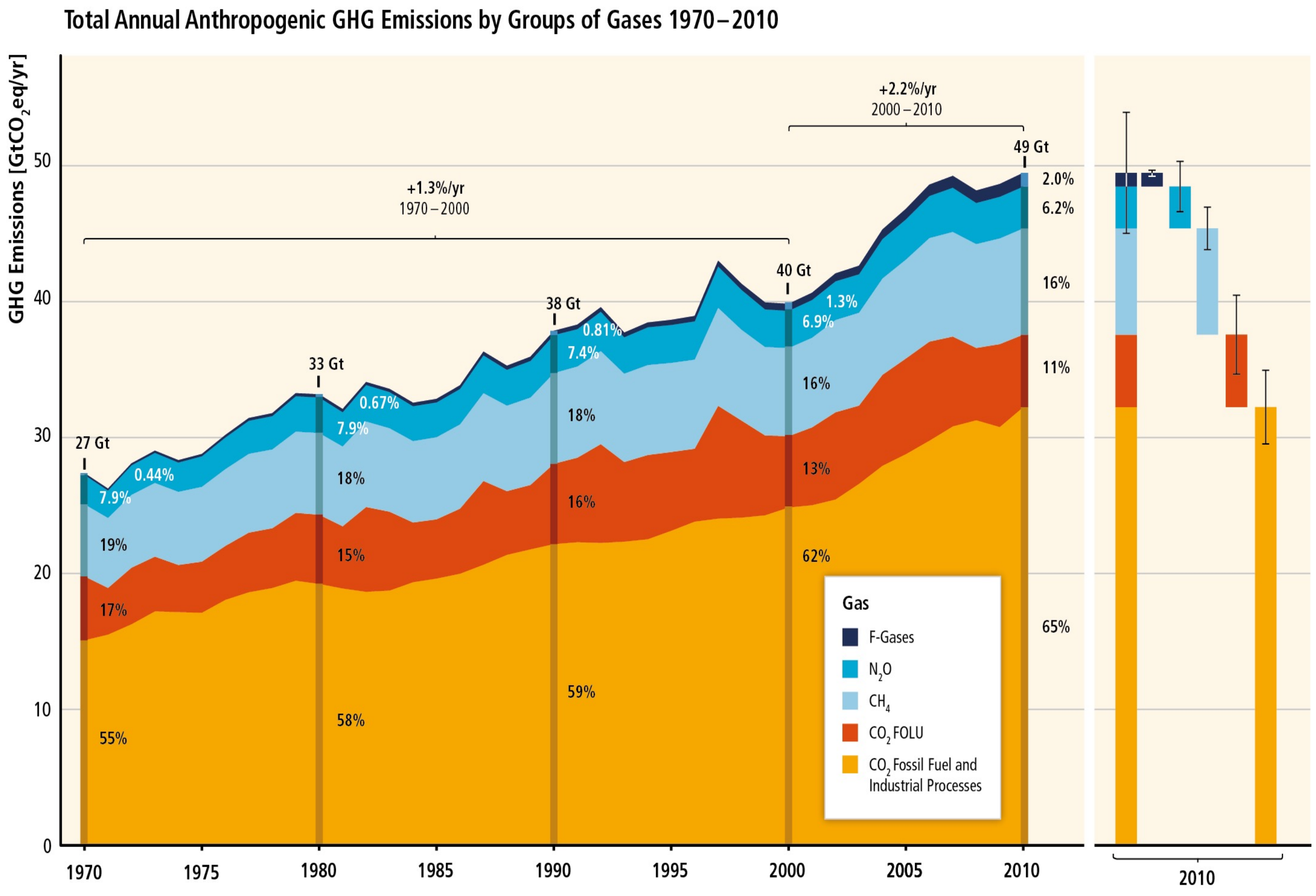
Fossil fuels

- Continuous increase since 1800s
- In 2010 the annual output was around 10.000 million tons of oil equivalents.
- In 2018, global energy consumption consisted of oil (34%), coal (27%) and natural gas (24%).

Fossil fuels

Environmental impact

- Combustion of fossil fuels releases carbon dioxide (CO2) into the atmosphere
- Increase of radiative forcing, adding to global warming
- 65% of anthropogenic greenhouse gases emissions is CO2 from fossil fuels



Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970–2010

Figure 1-5: Total annual anthropogenic GHGs emissions by type 1970-2010.

Fossil fuels

Environmental impact

- Emissions of benzene, formaldehyde from wells, transport, processing facilities
- Emissions of sulfur dioxide, mercury, particulate matter, carbon monoxide, nitrogen oxide
- Impact on water and oceans due to mining, fracking, extraction and transport
- Risks of spills, leaks, pollution of freshwater and ocean ecosystems
- Acidification of ocean due to carbon absorption
- Fossil fuel infrastructure changes entire landscapes and ecosystems

Fossil fuels

- Hubbert peak theory predicted oil production peak in the '70s in the USA
- Production follows a bell-shaped curve
- Increase of oil imports during periods of decreased production
- Production increases again due to technology advances
- Predicted peaks for natural gas and coal production in 2035 an 2052, respectively

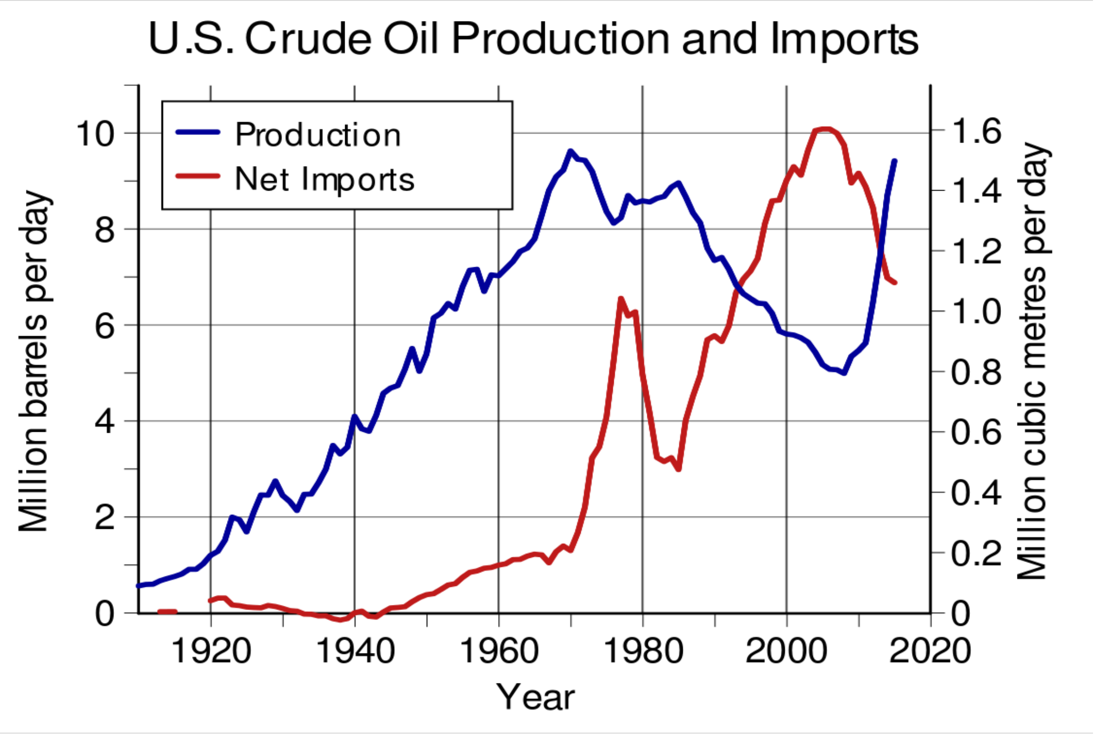


Figure 1-6: United States crude oil production and imports by year in millions of barrels per day.

Renewable Energy

- Infinite resources
- Reduction in anthropogenic emissions of greenhouses gases and pollutants
- Availability worldwide
- Safety and independence in energy production
- Technological advancements keep reducing renewable energy costs

Renewable Resources Types

- Solar energy
- Wind energy
- Bioenergy
- Geothermal energy
- Hydropower
- Marine energy

Renewable Energy

Solar Energy

- Photovoltaics
- Concentrated Solar Power
- Solar Thermal Heating and Cooling

Solar Energy

Photovoltaics

- Conversion of solar energy to electricity
- PV cell is a semiconductor (silicon)
- PV module formation from interconnection of PV cells
- PV module connection with batteries, electrical components, mounting systems etc. to form PV system
- Production of power from a few watts to tens of megawatts

Solar Energy

Photovoltaics

- The band energy gap between valance and conduction band is small in a semiconductor
- Electrons leave the valance band, leaving behind a hole
- Movement of electrons (negative) and holes (positive) result in current
- Silicon can be doped with phosphorus (negative-type semiconductor) or boron (positive-type semiconductor) to increase conductivity

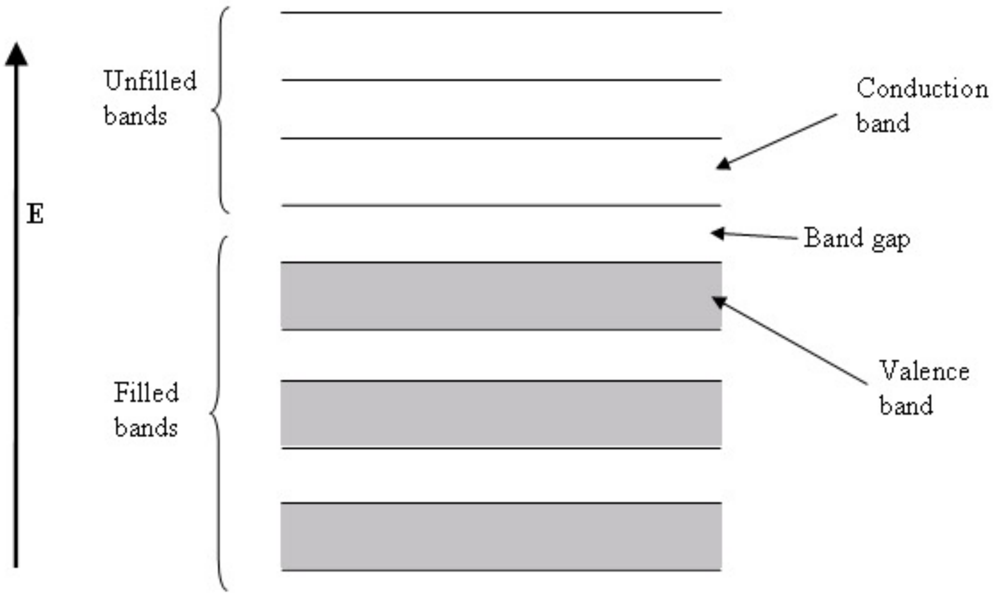
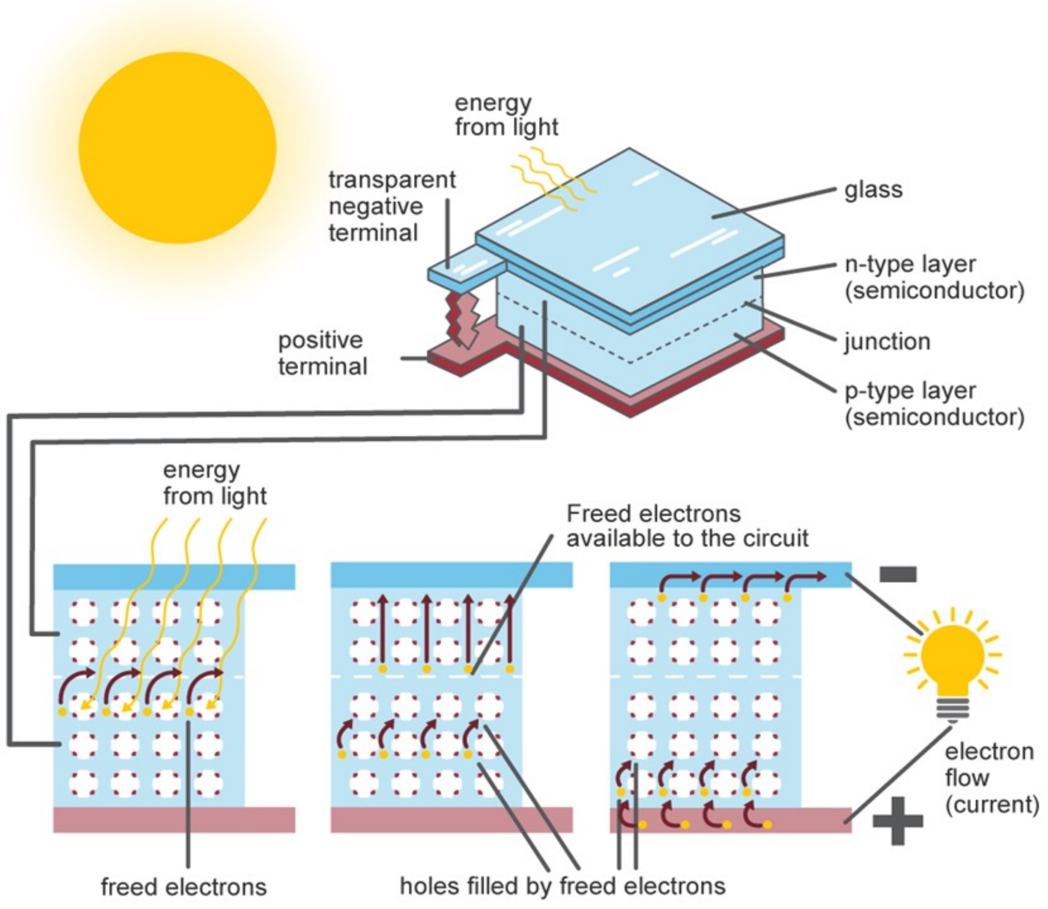


Figure 1-7: Energy band structure of a semiconductor.

Solar Energy

Photovoltaics

- Creation of electric field and current in a photovoltaic cell
- Materials should have band gap energies in the visible range
- Excess energy, after the movement of electrons to the conduction band, becomes heat



Source: U.S. Energy Information Administration

Figure 1-8: Depiction of a photovoltaic cell.

Solar Energy

Photovoltaics

- PV systems in operation have an efficiency of 7-17%
- Multiple p-n junctions and low temperatures improve the efficiency
- Cell types include single crystal, semicrystalline, thin film, amorphous, polycrystalline thin films
- PV systems use both direct and diffuse radiation, so they can operate on cloudy days

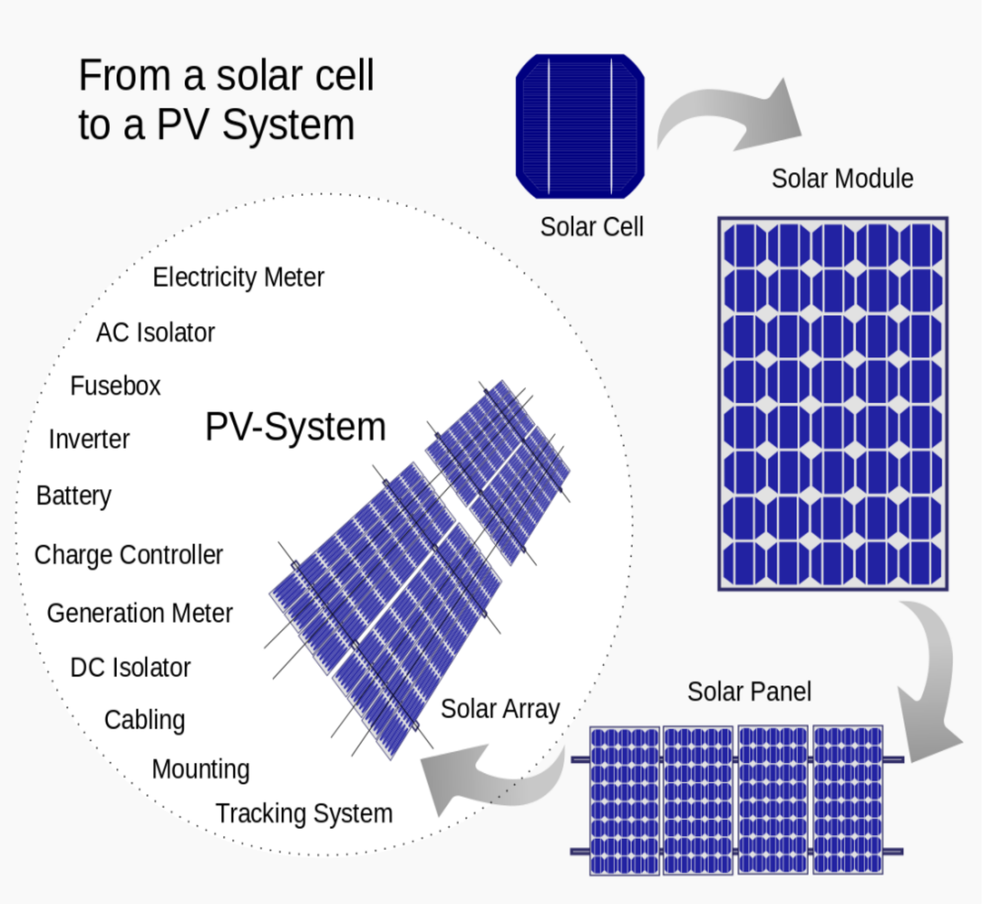


Figure 1-9: From a solar cell to a PV system.

Solar Energy

Photovoltaics

- PV can be in a fixed position or use a tracking system
- Azimuth angle is south (N.Hemisphere) and tilt angle is the latitude
- Off-grid or grid-connected installations
- Grid-connected PV systems can be used for residential, industrial, utility power purposes.
- Off-grid systems in use in remote areas, away from power lines and developing countries

Solar Energy

Photovoltaics

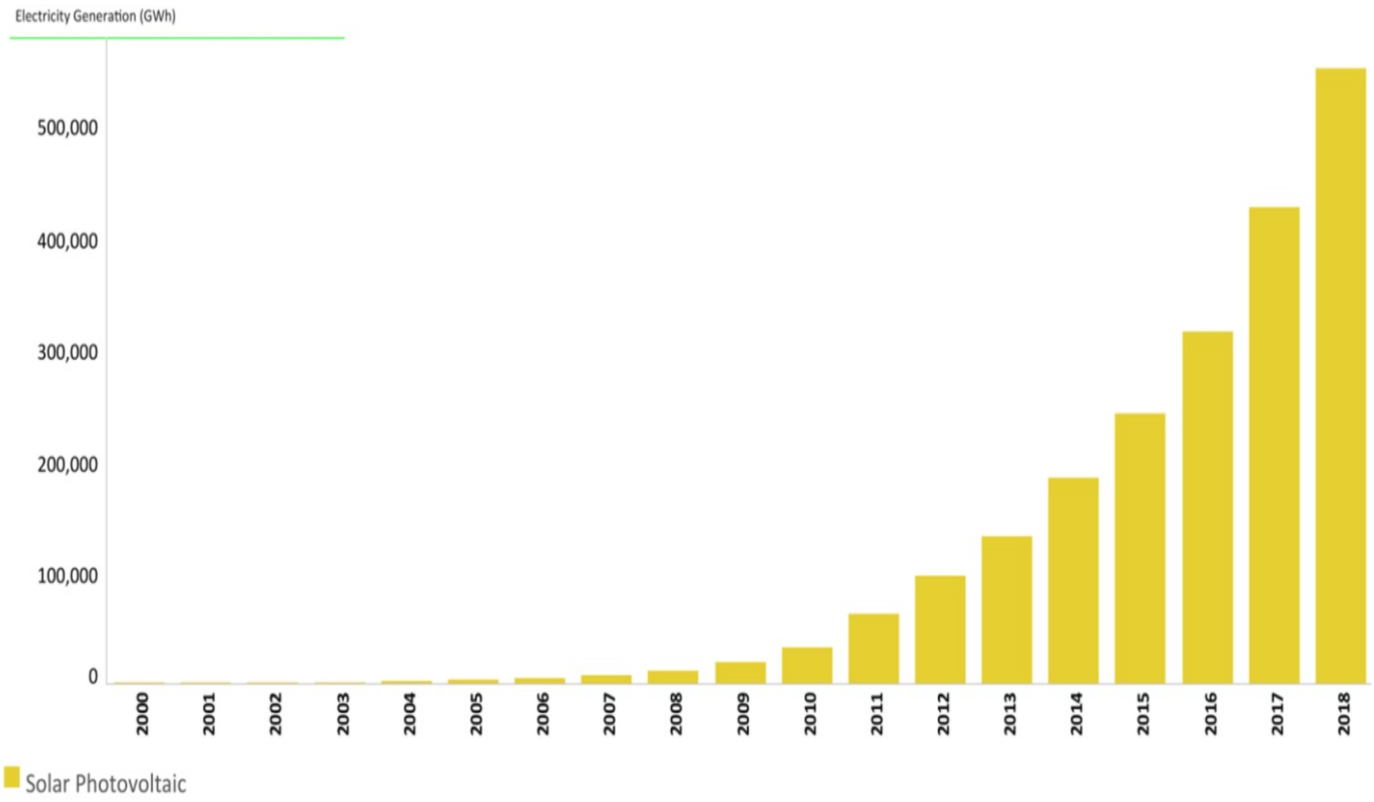


Figure 1-10: Worldwide electricity generation (GWh) from solar PV systems, from 2000 to 2018.

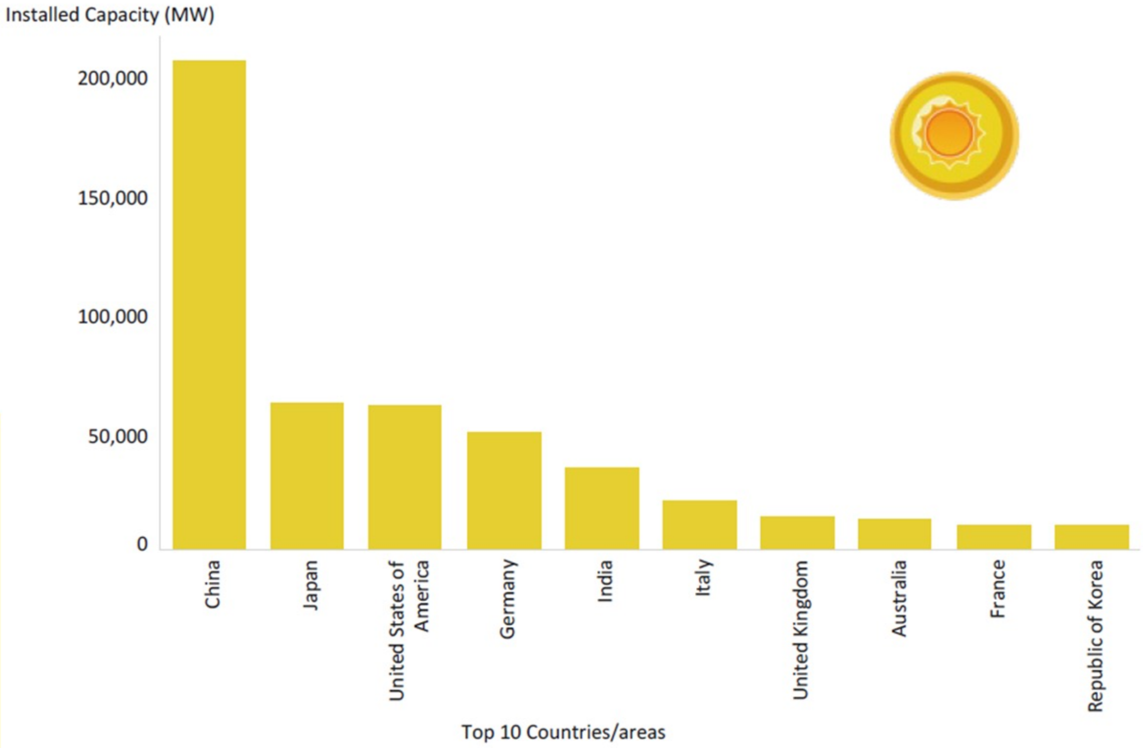


Figure 1-11: Installed PV capacity (MW) for the top 10 countries, for 2019.

Solar Energy

Concentrating Solar Power

- Concentrating solar power (CSP) systems use direct solar radiation for electricity production
- Mirrors or lenses concentrate radiation onto a receiver, radiation is converted to thermal energy, used for electricity generation
- Ability of thermal energy storage systems
- CSP plants may use natural gas to supplement energy

Solar Energy

Concentrating Solar Power

CSP types

- Power tower
- Linear focus
  - *Parabolic trough*
  - *Fresnel lenses*
- Dish/engine

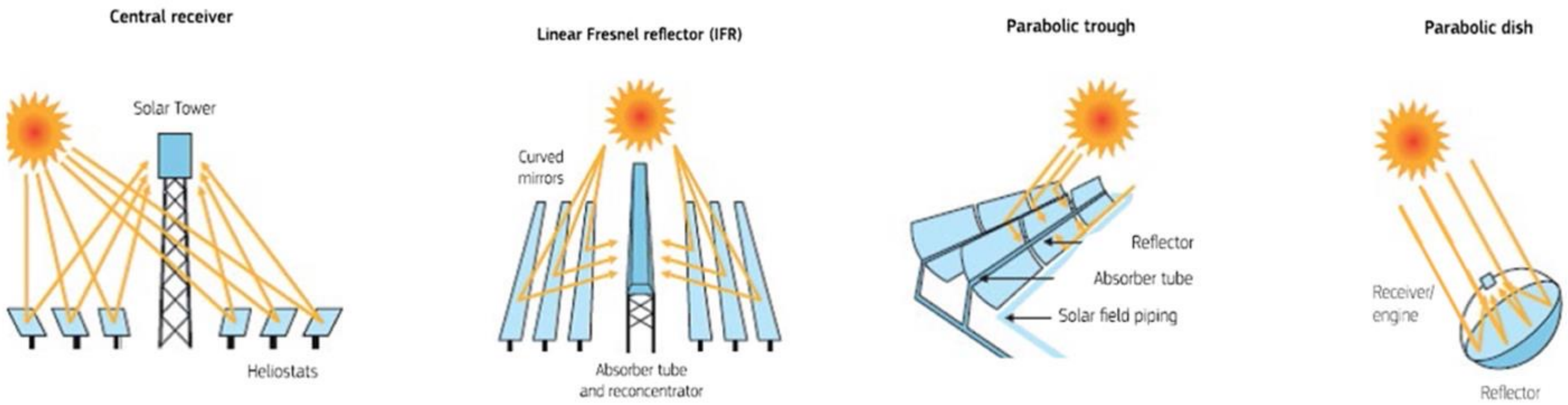


Figure 1-12: Concentrating solar power types: central receiver (solar power tower), linear Fresnel reflector, parabolic trough concentrator and parabolic dish concentrator.

Solar Energy

Concentrating Solar Power

Power Tower

- Power tower systems use heliostats to track and focus sunlight on a receiver on top of a tower
- The high energy concentrated beam is absorbed by a fluid, which is used to generate steam to drive a conventional turbine
- Fluids with high heat capacity and energy storage ability
- Power tower can operate on cloudy days or at night
- Power tower facilities cover large areas, up to 3 million square meters

Solar Energy

Concentrating Solar Power

- National Solar Thermal Test Facility, USA, power tower of 61m and 218 heliostats
- Abengoa towers in Spain, 11 and 20 MW installed maximum capacity
- Ashalim Power Station, Israel, power tower of 260m, 121 MW
- Crescent Dunes Solar Energy Project, USA, 125 MW
- Ivanpah Solar Power Facility, USA, 3 power towers, 392 MW
- Mohammed bin Rashid Al Maktoum Solar Park, UAE, tallest power tower at 262.44m

Power Tower

Figure 1-13: National Solar Thermal Test Facility.

- Ouarzazate Solar Power Station, Morocco, largest CSP plant, parabolic trough and power tower, 510 MW (phase 3)
- Tower at 150 MW most powerful built

Solar Energy

Concentrating Solar Power

Linear Focus – Parabolic trough

- Line focus systems use parabolic troughs or linear Fresnel reflectors to focus sunlight
- Aligned on a north-south axis, rotates to track sun movement
- Parabolic trough is lined with mirrors tc concentrate radiation along the focal line to a fluid-containing tube (water, molten salt, synthetic thermal oil)
- Fluid is heated and driven to a heat engine for electricity generation

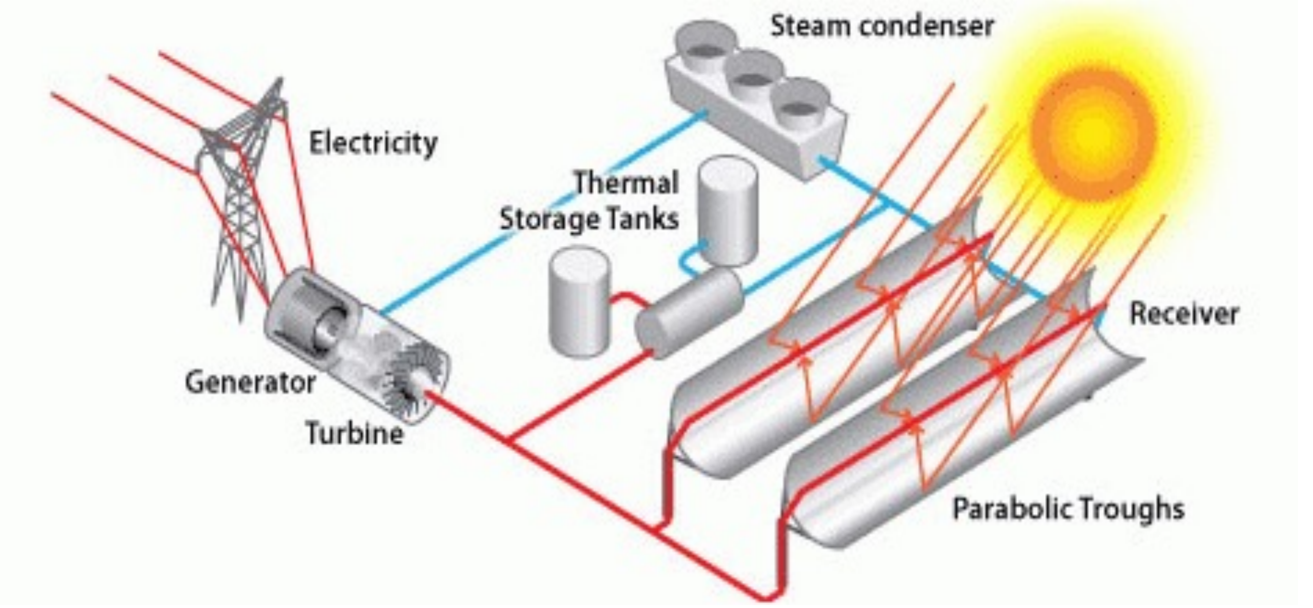


Figure 1-14: Diagram of a parabolic trough system.

Solar Energy

Concentrating Solar Power

Linear Focus – Parabolic trough

- Efficiency similar to photovoltaics
- Heat storage facilities, molten salt can be used as heat storage fluid
- Solar Energy Generating Systems (SEGS), California, combined capacity of 310 MW
- Solar Generating Station, Arizona, capacity of 280 MW
- Genesis Solar Energy Project, California, capacity of 250 MW
- Solaben and Andasol Solar Power Stations, Spain, capacities of 200 and 150 MW

Figure 1-15: Parabolic troughs at the SEGS plant, USA.

Solar Energy

Concentrating Solar Power

Linear Focus – Fresnel reflector

- Linear Fresnel reflector, based on Fresnel lens
- Long, thin rows of mirrors, which focus sunlight onto a downward facing linear receiver
- Receiver in a fixed position, reflectors have one or two-axis tracking system
- Concentrated energy is transferred to a thermal fluid (synthetic oil), lead to a steam turbine
- Thermal fluid can be used for heat storage

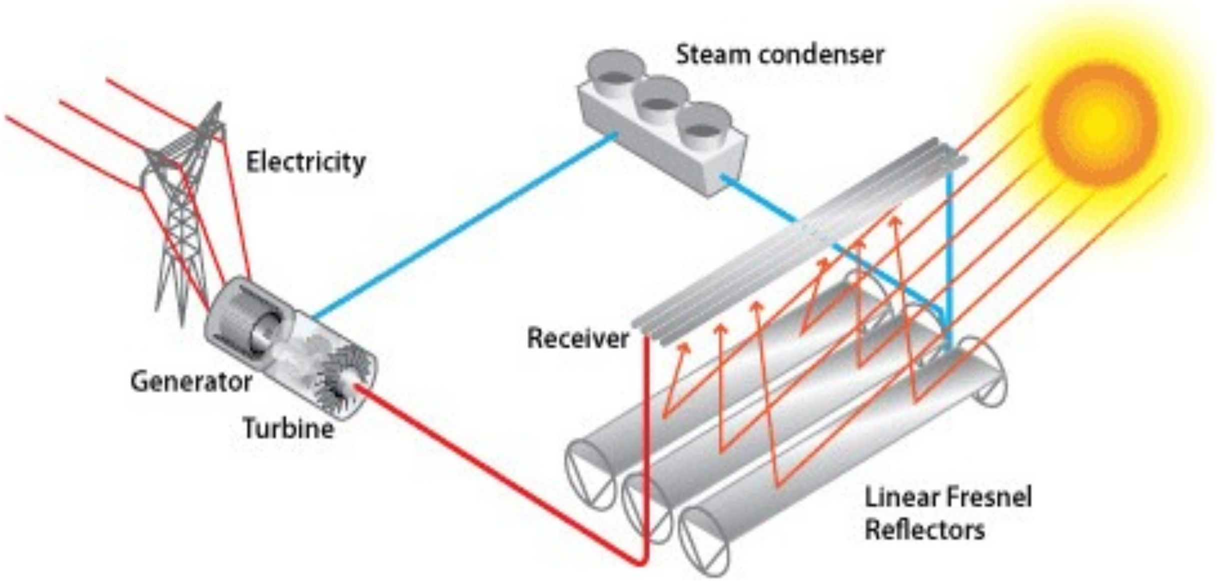


Figure 1-16: Diagram of a linear Fresnel reflector system.

Solar Energy

Concentrating Solar Power

Linear Focus – Fresnel reflector

- Kimberline Solar Thermal Energy Plant, California, first Fresnel reflector commercial plant, capacity 5 MW
- Puerto Errado 1 (PE 1), Spain, capacity 1.4 MW
- Reliance Power plant, India, largest CSP system with Fresnel reflector technology, capacity 125 MW

Figure 1-17: Linear Fresnel reflector technology at Puerto Errado 1 solar thermal power plant, Spain.

Solar Energy

Concentrating Solar Power

Dish/engine

- Dish/engine system consists of a parabolic dish, made from mirrors
- Sunlight is focused on a thermal receiver at the focal point
- Receiver transfers heat to the heat engine (Stirling engine)
- Stirling engine: cyclic compression and expansion of gaseous working fluid at different temperatures results in conversion of heat to mechanical power to run a generator
- Dish Stirling systems have the highest capacities of solar technologies

Solar Energy

Concentrating Solar Power

Dish/engine

- Dish Stirling at Sandia's National Solar Thermal Test Facility achieved 31.25% efficiency
- Maricopa Solar power plant, Arizona with capacity of 1.5 MW
- Plataforma Solar de Almeria, Spain, two dish Stirling systems designed under EUROdish project

Figure 1-18: EUROdishes at Plataforma Solar de Almeria.

Solar Energy

Solar Thermal Heating and Cooling

- Solar heating cooling technologies provide hot water, space heating and cooling, process generated heat
- Active systems usually have the solar collector and storage separate from the building
- Passive systems are building designs to maximize incoming solar heat or space light

Solar Energy

Solar Thermal Heating and Cooling

Active heating

- Active heating needs pumps or fans to move the heat transfer fluid
- In solar hot water system, space can be heated by radiant water heaters or air heating
- In solar hot air system, larger volume of air is needed to provide same heat
- Flat-plate collectors are used, placed at an angle

Solar Energy

Solar Thermal Heating and Cooling

Active heating

- Flat-plate collectors for space heating, domestic hot water
- Consist of a collector surface, glazing, heat transfer fluid, insulation
- Heat transfer fluid transfers heat to a separated reservoir
- Absorbing surface of copper, iron or aluminum
- Glazing plastic or glass

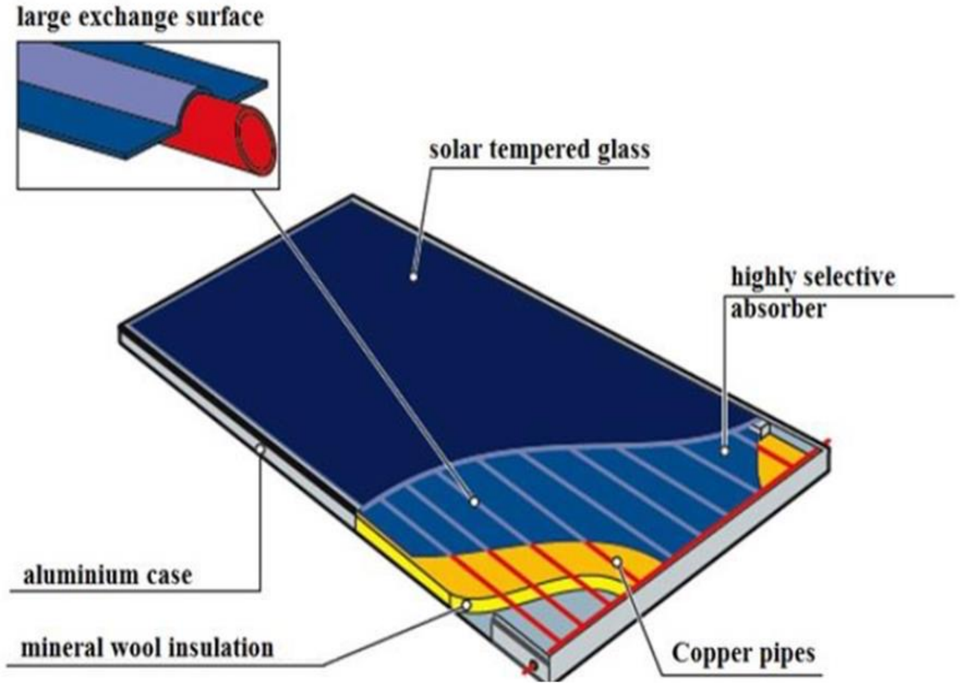


Figure 1-19: Diagram of a flat-plate collector.

Solar Energy

Solar Thermal Heating and Cooling

Active heating

- An evacuated tube collector consists of single parallel glass tubes, which surround the absorber
- Tubes are evacuated to reduce heat loss
- Increased efficiency as rays always perpendicular to surface
- Tube consists of an outer transparent and inner selective absorbing glass tube, with the absorber inside the inner tube

Figure 1-20: An evacuated tube collector.

Solar Energy

Solar Thermal Heating and Cooling

Active heating

- Outer tube allows sunlight, inner tube minimal reflective
- Air between tubes is evacuated
- Heat transfer fluid flows in and out of the tubes or the tubes are connected to heat pipes
- Heat pipes transfer heat to a fluid in a heat exchanger
- Tubes absorb infrared, operate in cloudy, windy or cold days

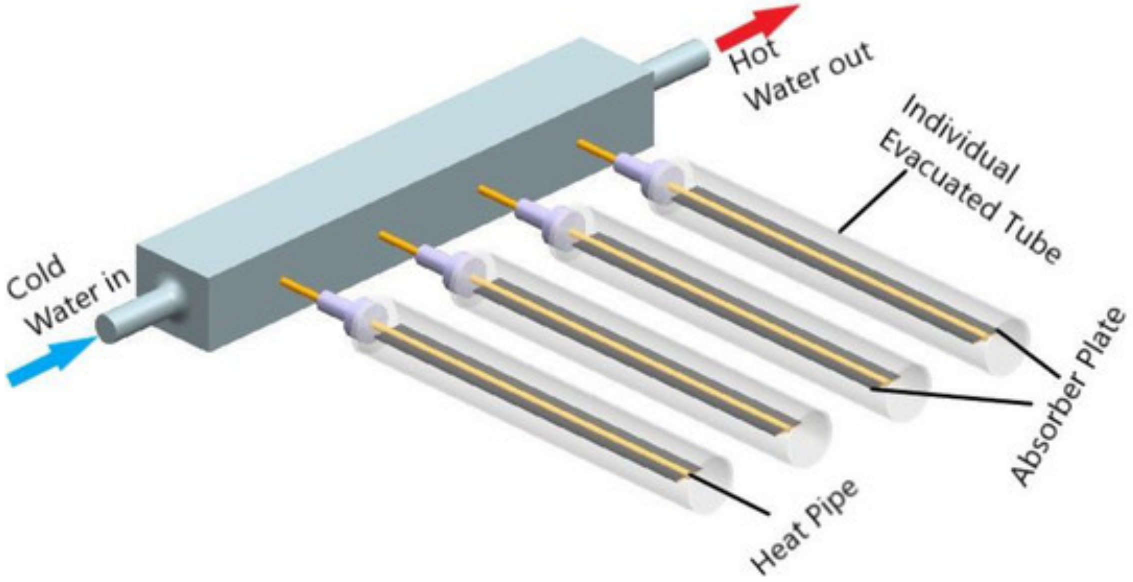


Figure 1-21: A heat pipe evacuated tube collector.

Solar Energy

Solar Thermal Heating and Cooling

Active cooling

- Active solar systems with absorption cooling unit are used for space cooling
- Unit uses two fluids, an absorbent (water) and a refrigerant (ammonia)
- Refrigerant performs evaporative cooling and is absorbed by the absorbent

Solar Energy

Solar Thermal Heating and Cooling

Passive heating and cooling

- In passive solar systems, buildings or parts of them are designed to collect, store and distribute energy, for heating in summer and cooling in winter
- Main factors are size and placement of windows, glazing, shading, thermal mass, insulation, orientation, shape and colour, vegetation
- Diffuse component desirable throughout the year
- Direct component in winter

Solar Energy

Solar Thermal Heating and Cooling

Passive heating and cooling

- Windows positioned vertically for less sunlight
- Shading for south facing windows in summer
- Double pane windows for cold climates
- Large thermal mass reduces temperature variations
- Direct solar gain when sunlight is absorbed where it enters
- Indirect gain when there is transfer to the rest of the structure (convection, conduction, radiation)

  examples: solarium, greenhouse, Trombe wall

Solar Energy

Solar Thermal Heating and Cooling

Passive heating and cooling

- Trombe wall: masonry wall, thick, coated with dark colour material, absorbs solar thermal energy
- Covered with glass outside
- Air insulation between wall and glaze
- Solar radiation is absorbed by dark coated outer surface
- Heat is trapped between glaze and outer surface, conducted through the masonry and distributed to space
- Time delay in heat transfer

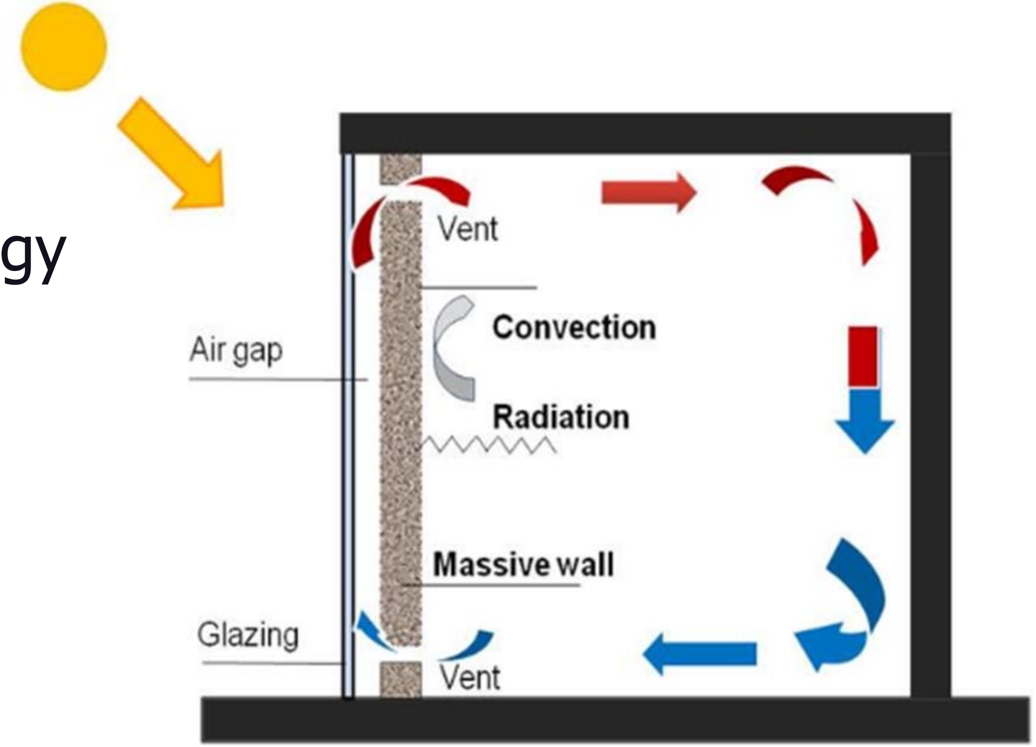


Figure 1-22: Diagram of a Trombe wall.

Solar Energy

Solar Thermal Heating and Cooling

Passive heating and cooling

- Passive cooling is the procedure of replacing hot air with cooler air
- A building’s thermal mass can be ventilated at night
- Use of thermal chimneys
- Low south facing and high north facing windows can produce a current for cooling the space

Wind Energy

- Wind turbines produce mechanical energy to turn electric generators
- Variations in wind resource
- Wind power used throughout history to sail ships, grind grain, pump water
- Windmills extensive use in mid-1900s
- Oil crisis of 1973 lead Denmark, USA to implement construction of large wind generators to connect to the grid
- From 2009 wind power is developed in many countries
- Installed capacity in USA reached 60 GW in 2012
- Wind energy installations range from small projects to big wind farms

Wind Energy

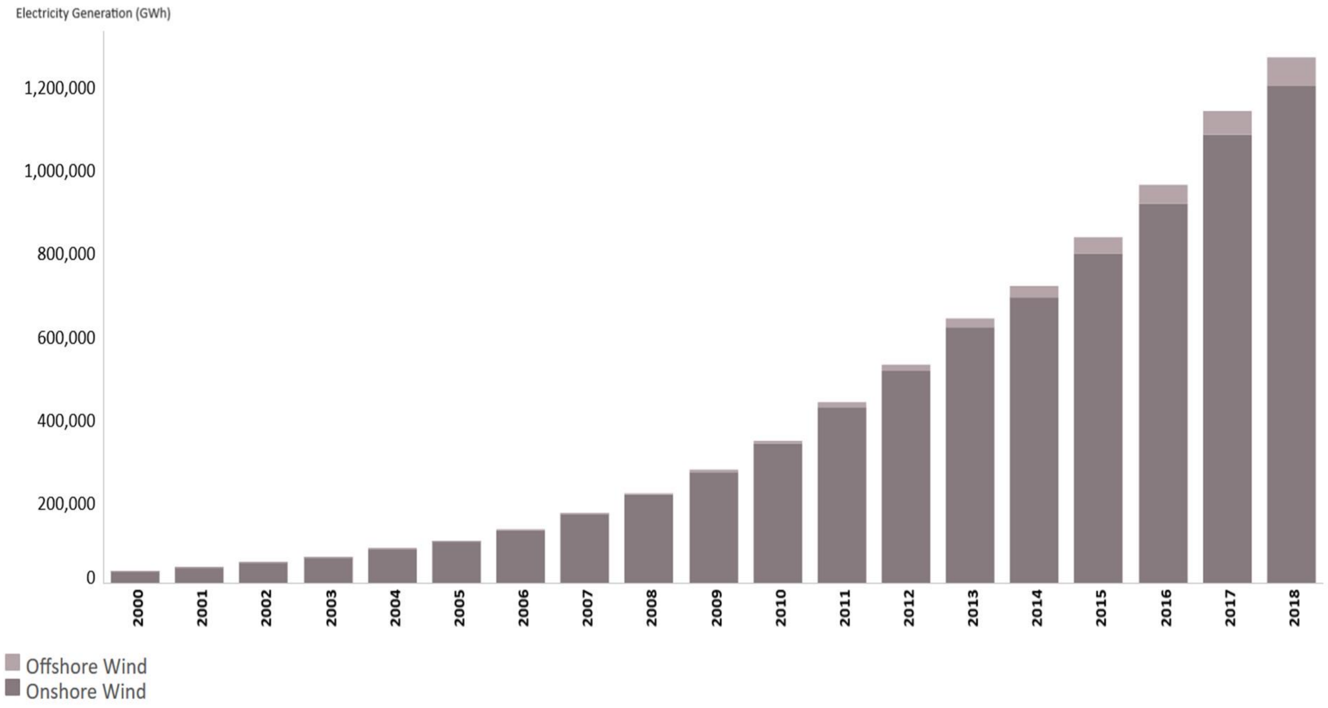


Figure 1-23: Electricity generation (GWh) from wind power, 2000 – 2018.

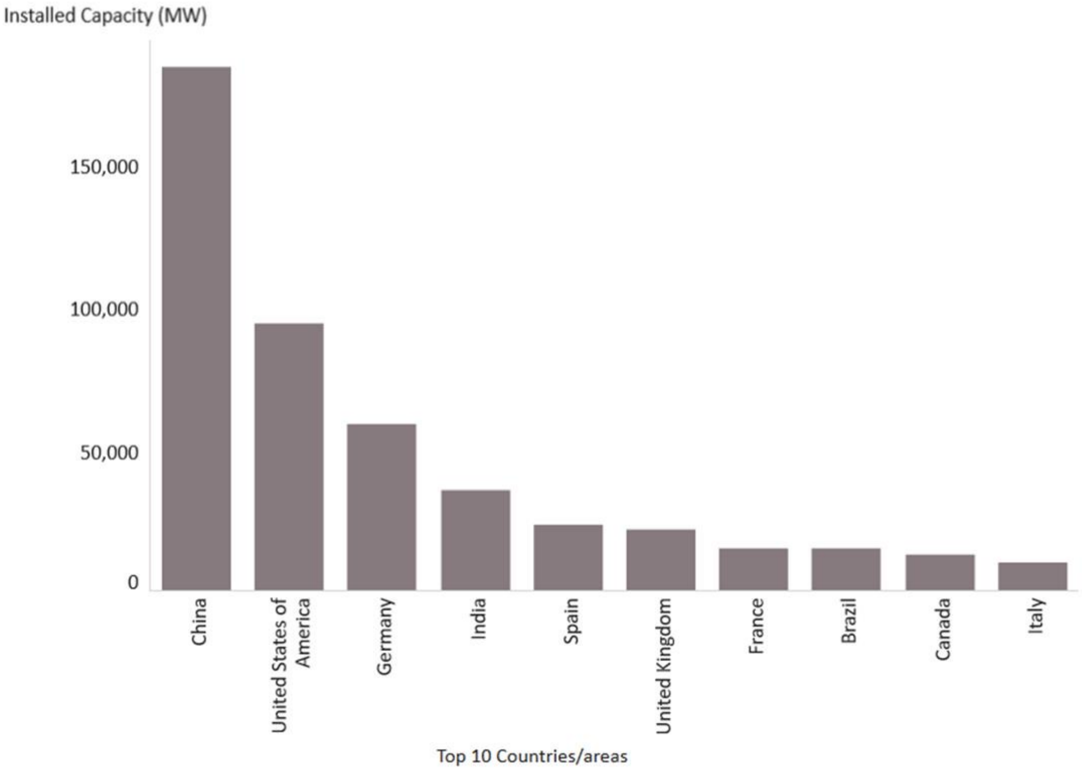


Figure 1-24: Installed wind power capacity (MW) for top 10 countries, for 2018.

Wind Energy

- Wind power density is power P per unit area A

$$\frac{P}{A} = 0.5 * \rho * v^3, \qquad W/m^2$$

ρ,v the air density and wind speed

- Wind shear important in wind power installations

$$\frac{v}{v^0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

α the wind shear exponent

- Wind resource assessment is needed
- Wind power maps, GIS data, software tools
- Ground-based wind speed measurements

Wind Energy

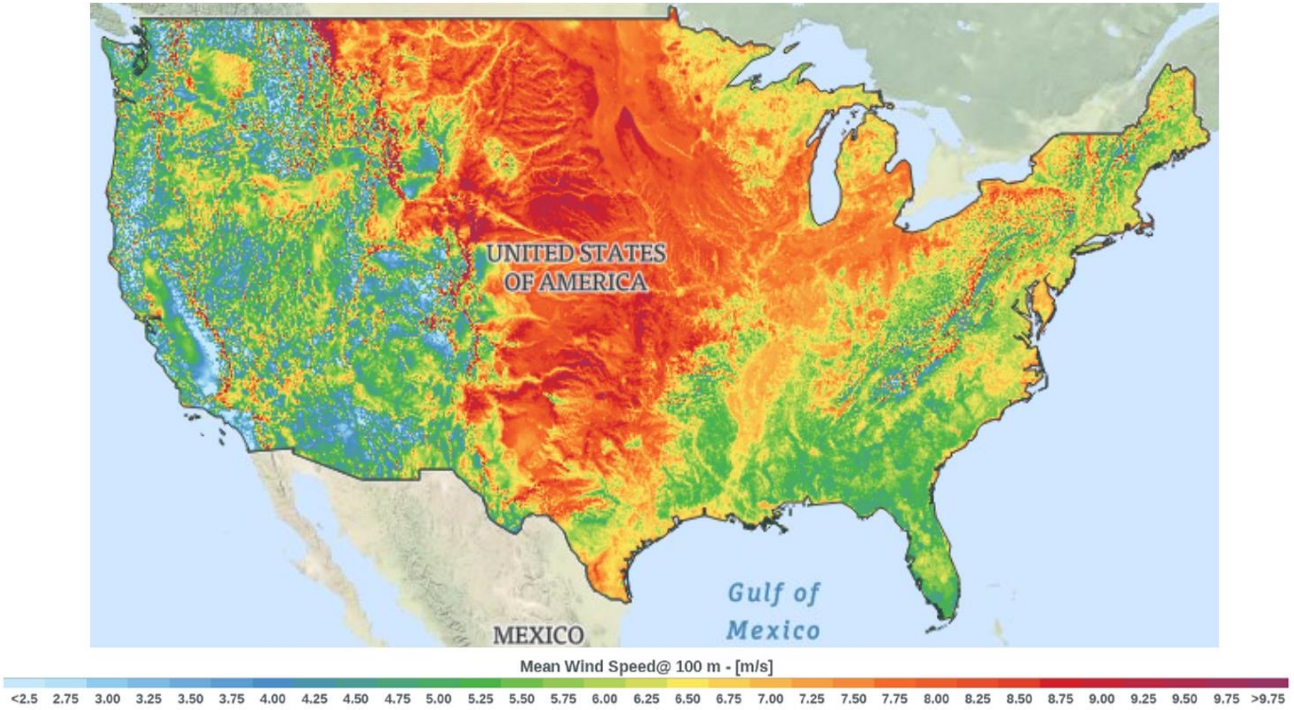


Figure 1-25: Wind map of mean wind speed (m/s) at 100m, for the USA.

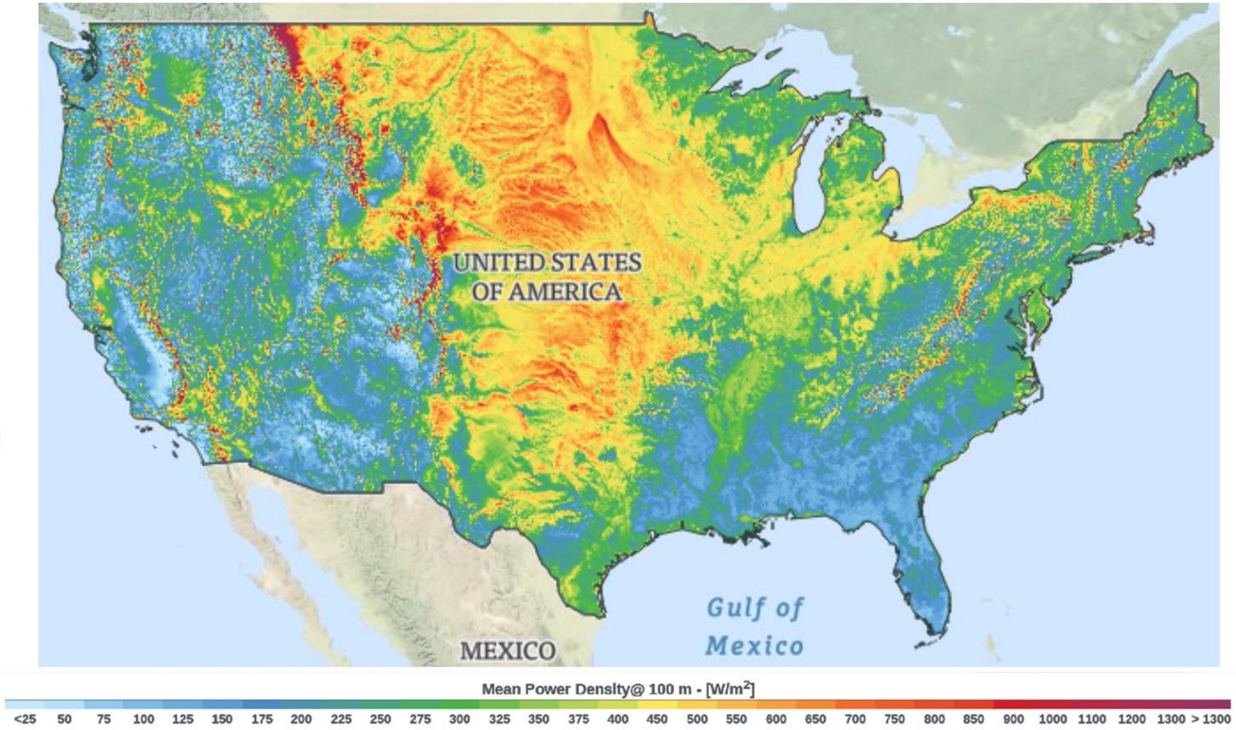


Figure 1-26: Wind map of mean power density (W/m^2) at 100m, for the USA.

Wind Energy

Wind Turbines

- Wind turbines convert kinetic energy into electrical energy
- Sizes vary: small devices, larger for domestic power supply, arrays of turbines for grid power
- A large wind turbine consists of the rotor, the gearbox to increase blade rotation, conversion system (generator), controls, installation’s tower

Wind Energy

Wind Turbines

- Two types based on the aerodynamic force used for extraction of wind energy

- **Drag-based turbines**:

  the rotor turns on its axis, blade speed can't exceed wind speed

- **Lift-based turbines**:

  airfoil surfaces, blades move perpendicular to wind flow

  blades speeds higher than wind speed, more efficient

Wind Energy

Wind Turbines

- Two types based on the orientation of the turbine rotor axis with the ground

  - Horizontal axis wind turbines (HAWT)
  - Vertical axis wind turbines (VAWT)

Wind Energy

Wind Turbines

Horizontal axis

- HAWTs can be upwind (rotor facing the wind) or downwind (rotor on the lee side of the tower)
- Yaw mechanism to keep rotor perpendicular to the wind
- HAWTs with three blades, upwind, the most common in installations worldwide

Figure 1-27: Horizontal axis wind turbine.

Wind Energy

Wind Turbines

Vertical axis

- ○ VAWTs have a vertical rotor axis
- ○ Don’t need to face the wind to operate
- ○ Gearbox, generator can be placed at ground level
- ○ Lower efficiency than HAWTs
- ○ Not used for large scale electricity generation

Two main types of VAWTs

- ➢ *Darrieus turbine*
- ➢ *Savonius turbine*

Wind Energy

Wind Turbines

Vertical axis - Darrieus

- Darrieus turbine is a lift-based turbine
- Curved aerofoil blades on a rotating axis
- Blades need higher speed than wind speed to produce power
- Doesn’t self start

Figure 1-28: Darrieus wind turbine.

Wind Energy

Wind Turbines

Vertical axis - Savonius

- Savonius turbine is a drag-based turbine
- Aerofoil blades with semi-circular shape, mounted on a rotating shaft
- Can self start
- Lower efficiency than Darrieus turbine
- Popular for water pumping, grain grinding

Figure 1-29: Savonius wind turbine.

Wind Energy

Wind Turbines

Vertical axis

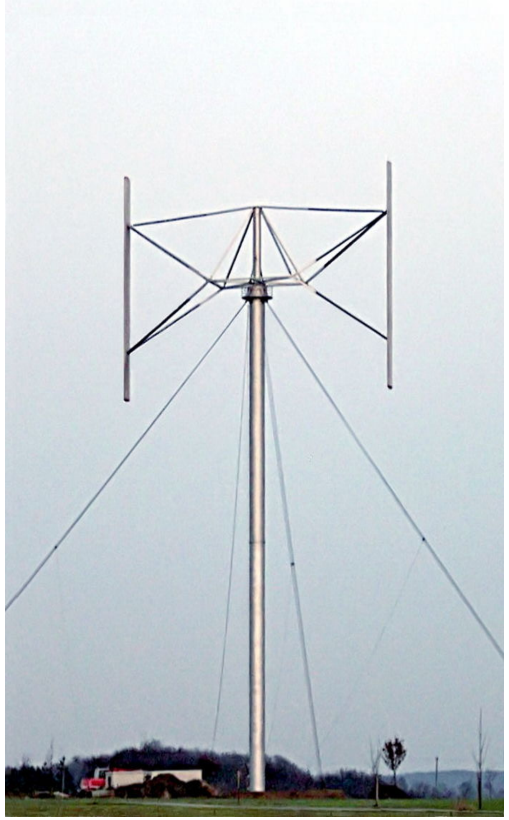


Figure 1-30: Giromill or H-rotor wind turbine.

Figure 1-31: Combination turbines of Darrieus and Savonius designs in Jinguashi, Taiwan.

- Giromill or H-rotor turbine: same design as Darrieus but blades are straight vertical, connected to the tower with horizontal supports
- Turbines can be combinations of designs

Wind Energy

Wind Farms

- Wind farm is an assembly of wind turbines in an area, for electricity generation
- Small wind farm with several turbines
- Large wind farm with hundreds or even thousand wind turbines
- Onshore and offshore wind farms
- China, India, USA have the largest onshore wind farms

Wind Energy

Wind Farms

- Largest onshore wind farm is Gansu Wind Farm, China, 7965 MW capacity, target capacity of 20000 MW

- Largest offshore wind farm is Hornsea 1, UK, capacity of 1218 MW, 174 turbines

Figure 1-32: The onshore Gansu Wind Farm in China.

Figure 1-33: The offshore Hornsea 1 wind farm, in the UK.

Wind Energy

Wind Farms

- Site with favourable wind conditions, access to electric transmission, physical access
- High and consistent wind speeds
- No high turbulence
- Wind from one direction
- Site altitude and distance between turbines need to be determined

Wind Energy

Wind Farms

- First onshore wind farm in 1980, in New Hampshire, USA, capacity of 0.6 MW
- Other large onshore wind farms: Alta Wind Energy Center (Mojave Wind Farm), California, 1550 MW capacity
- Muppandal Wind Farm, India, 1500 MW
- Jaisalmer Wind Park, India, 1064 MW
- Los Vientos Wind Farm, Texas, USA, 912 MW
- Shepherds Flat Wind Farm, USA, 845 MW
- First offshore wind farm in Denmark in 1991
- Borssele 1&2, 3&4 (752 and 731.5 MW), Netherlands
- East Anglia ONE, UK, 714 MW
- Walney and London Array, UK, 659 and 630 MW capacity
- Gemini Wind Farm, Netherlands, 600 MW
- Hohe See, Germany, 497 MW
- In 2010, total offshore wind farm capacity in Europe was 2396 MW
- In 2019 global wind power capacity was 651 MW

Wind Energy

- No harmful emissions from wind power installations
- Effects on landscape and wildlife
- Visual impact and noise effects
- Small wind power projects (up to 50 kW) used in households, surplus can be sold to utility company
- Off-grid projects in remote areas
- Supplement other electric power sources

Bioenergy

- Bioenergy is produced from organic materials
- Biomass is organic material which has stored sun's energy through photosynthesis, combustion for energy production
- Renewable resource based on the carbon cycle
- Energy can be converted to heat, electricity or fuels (biofuels), which can be transported and stored
- Sources include wood, crops, municipal wastes, animal waste, manure, algae, bacteria, corn and soybeans (for biofuels)

Bioenergy

- Energy consumption from renewables at around 18% in 2017
- Biomass was the largest of the renewable resources in energy consumption

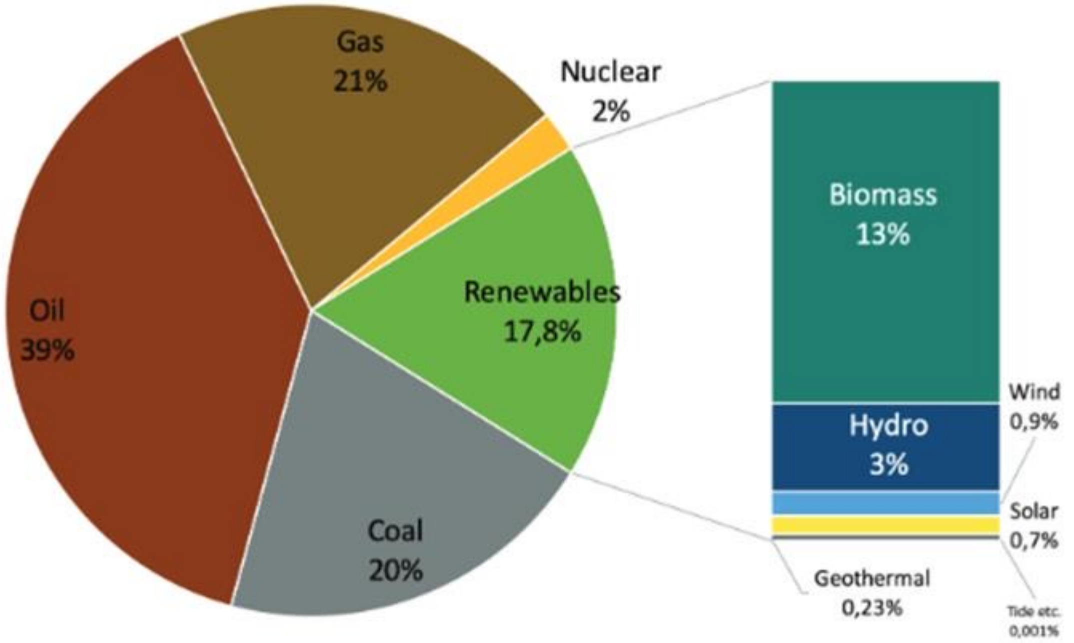


Figure 1-34: Total energy consumption for 2017.

Bioenergy

- Europe and Asia have the largest production of biomass power, majority comes from solid biofuels (woodchips, pellets etc.)
- Municipal waste and biogas are major sources in Europe
- Industrial waste important source in Asia

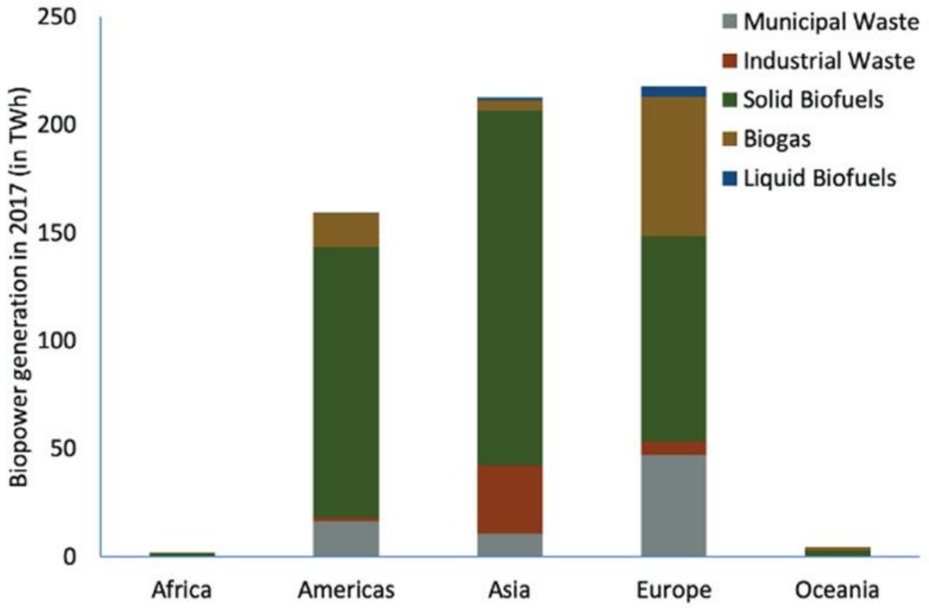


Figure 1-35: Biopower generation per continent for 2017.

Bioenergy

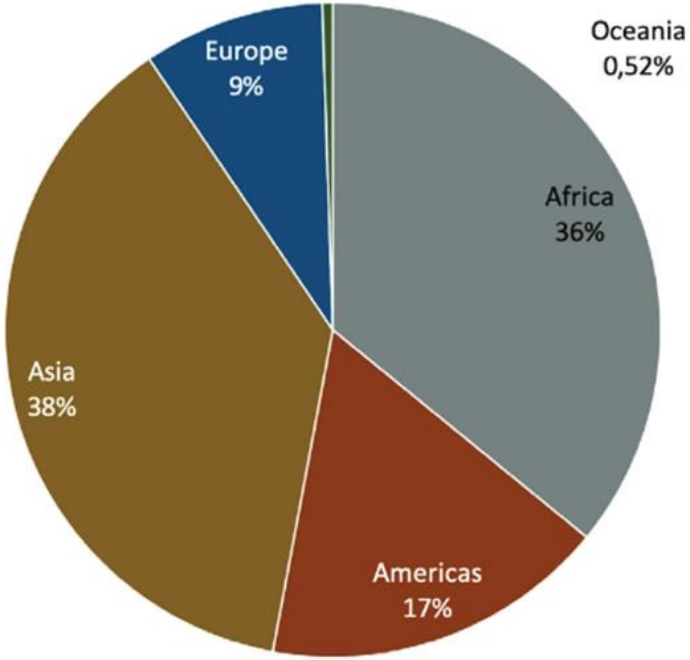


Figure 1-36: Woodfuel production per continent for 2018.

Figure 1-37: Wood pellets.

- Wood major energy source in developing countries, used for heating and cooking
- Processed to produce pellets
- Africa and Asia first in woodfuel production

Bioenergy

- Municipal solid waste (MSW), source of biomass, includes clothing, boxes, paper, food wastes etc.
- Industrial, agricultural, sewage wastes not included
- Landfills are huge sealed holes with compacted garbage
- Landfill gas is the gas produced in landfills from the decomposition of MSW
- Contains methane and carbon dioxide
- Direct heat production through combustion or electricity production via steam turbines, microturbines, fuel cells
- Puente Hills Landfill, USA 40 MW
- Sudokwon landfill gas power plant, South Korea, 50 MW

Figure 1-38: Aerial photo of the Puente Hills landfill in the USA.

Bioenergy

- Sewage sludge is another source of biomass
- Focus of research for energy production, especially in developing countries
- Conversion of sewage waste water into drinking water and electricity, with the use of solid sewage material as fuel
- Methane the main product of sewage
- Use of sewage material leads to reduction on landfill waste and atmospheric burden from produced gas

Bioenergy

Biofuels

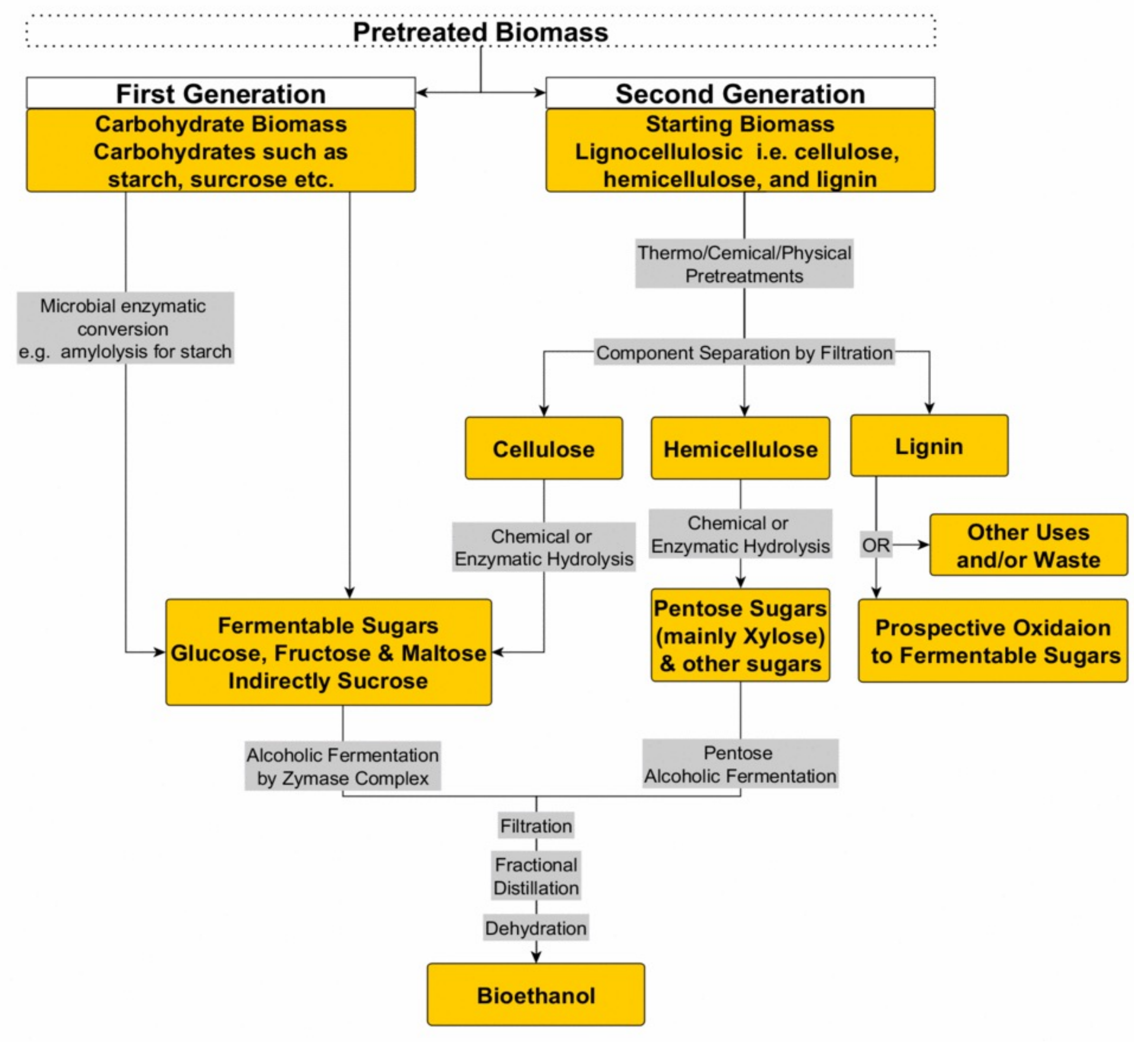
- Biofuels are the liquid or gas fuels produced from biomass processes
- They can be transported and stored
- Production from plants or agricultural, industrial, domestic organic waste
- Energy crops: plants grown for energy production
- Examples of biofuels: biogas, ethanol, biodiesel
- Renewable energy source since biomass can be replenished

Bioenergy

Biofuels

- Bioethanol produced from fermentation of sugars (corn, sugarcane, cellulose)
- Process includes enzyme digestion to release sugars, fermentation of sugars, distillation, drying
- Pre-treatment before entering fermentation stage

Ethanol



Pretreated Biomass

First Generation

Carbohydrate Biomass
Carbohydrates such as starch, surcrose etc.

Second Generation

Starting Biomass
Lignocellulosic i.e. cellulose, hemicellulose, and lignin

Microbial enzymatic conversion e.g. amylolysis for starch

Thermo/Cemical/Physical Pretreatments

Component Separation by Filtration

Cellulose

Hemicellulose

Lignin

Chemical or Enzymatic Hydrolysis

Chemical or Enzymatic Hydrolysis

OR

Other Uses and/or Waste

Fermentable Sugars
Glucose, Fructose & Maltose
Indirectly Sucrose

Pentose Sugars (mainly Xylose) & other sugars

Prospective Oxidaion to Fermentable Sugars

Alcoholic Fermentation by Zymase Complex

Pentose Alcoholic Fermentation

Filtration

Fractional Distillation

Dehydration

Bioethanol

Figure 1-39: Production diagram of first and second generation bioethanol.

Bioenergy

Biofuels

Ethanol

- Most known biofuel, popular in Brazil
- Replaces gasoline in petrol engines or mixes with it
- Bioethanol production 62% of total biofuel production in 2017
- USA, Brazil top countries in ethanol production
- Vehicles in USA use 10% ethanol mixture of gasoline, Brazil 25%

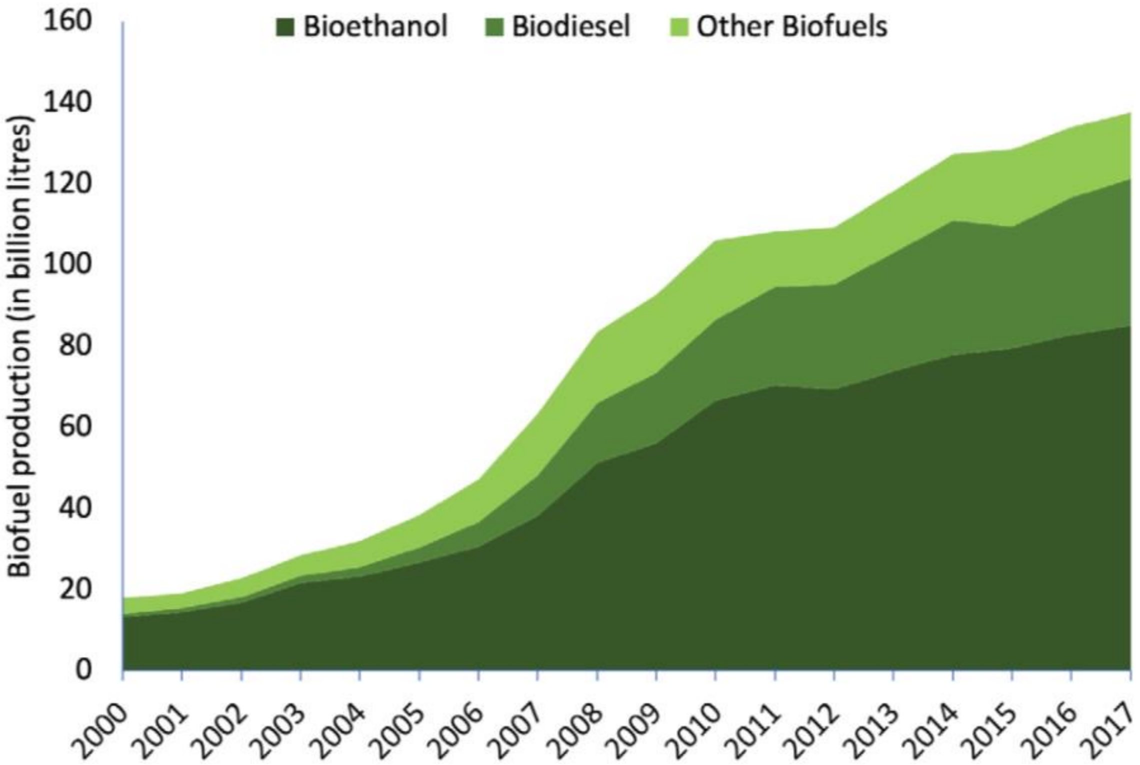


Figure 1-40: Global production of liquid biofuels.

Bioenergy

Biofuels

Biodiesel

- Biodiesel produced from vegetable oils, animal fats, recycled grease, fuel crops (e.g. palm oil)
- Production by transesterification, through which oils and fats are converted to biodiesel and glycerine
- Similar properties to petroleum diesel
- Can be used in diesel engines alone or mixed with petrodiesel

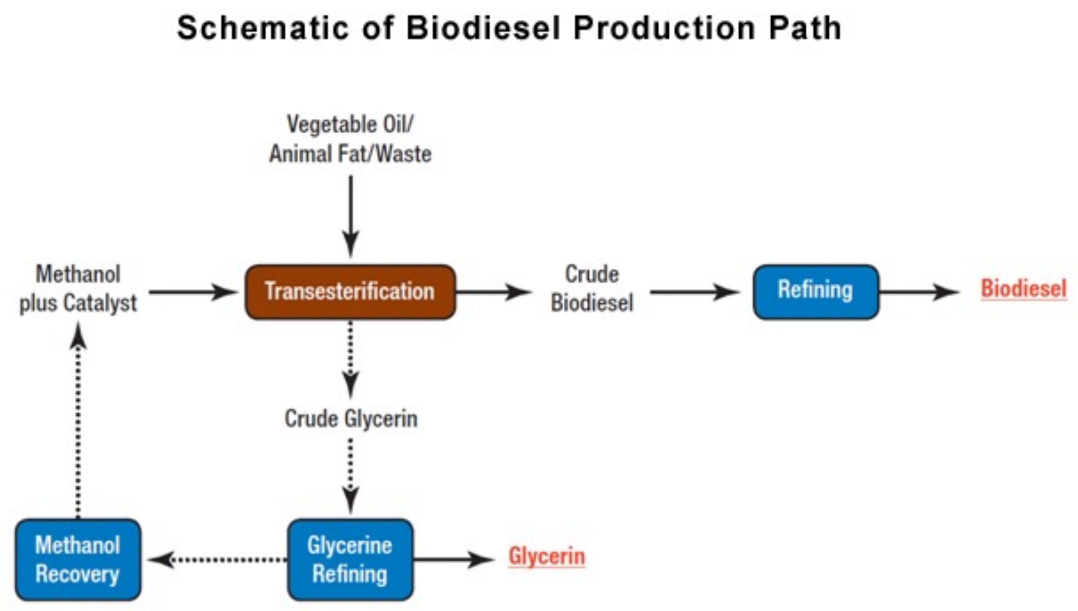


Figure 1-41: Diagram of biodiesel production process.

Bioenergy

Biofuels

Biodiesel

- Most common biofuel in Europe
- Lower carbon content and higher in hydrogen, oxygen compared to petroleum diesel
- Lower particulate emissions
- Higher nitrogen oxides emissions in pure biodiesel
- Biodiesel in fuel mix: B100, B20, B5, B2

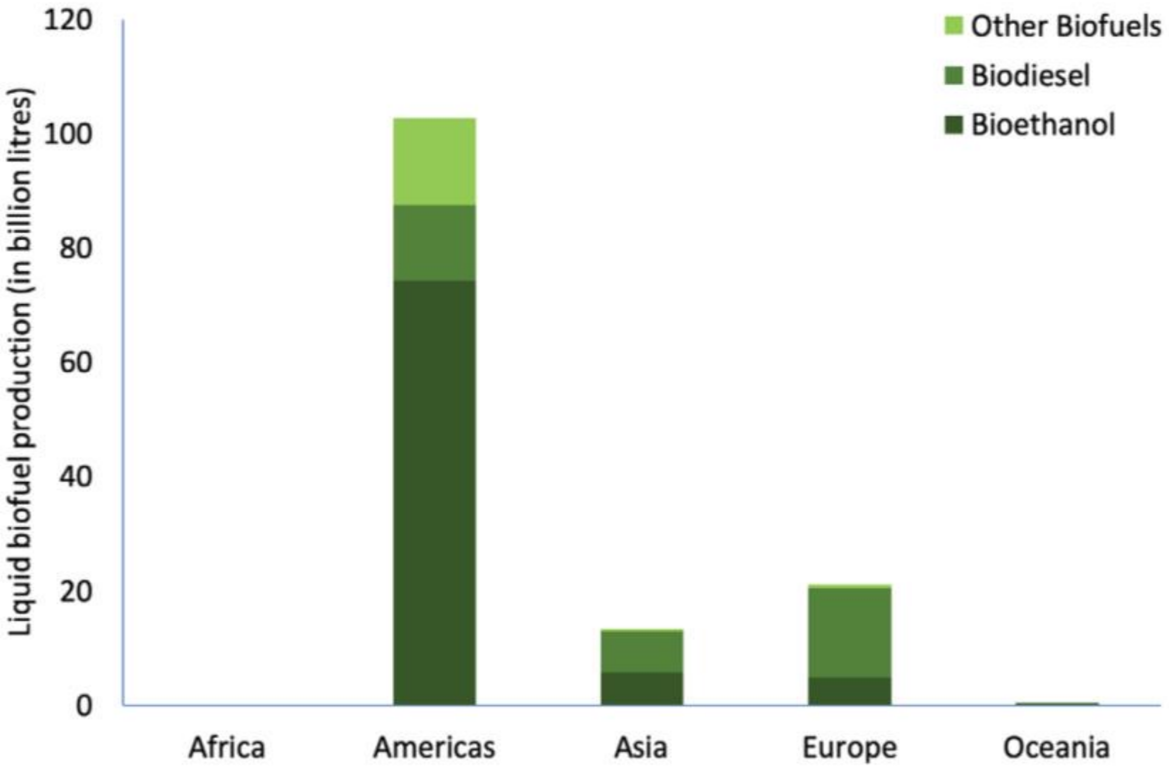


Figure 1-42: Liquid biofuels production per continent, in 2017.

Bioenergy

Biofuels

- Biogas produced by anaerobic digestion or fermentation of biodegradable materials, like manure, municipal waste, sewage, plants or energy crops
- Process takes place in a closed system, anaerobic digester or biodigester
- Consists mostly methane and carbon dioxide
- Biogas can be produced in landfills or biodigesters
- Europe is first in the production and use of biogas

Biogas

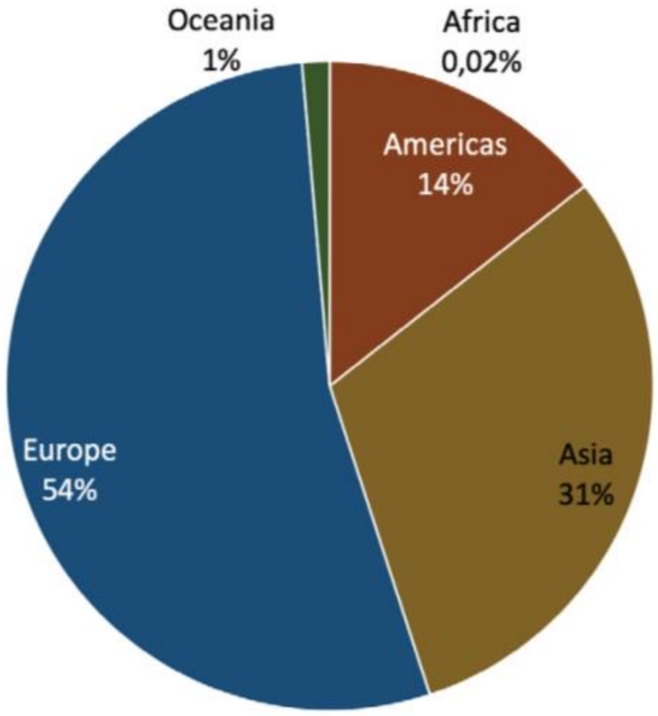


Figure 1-43: Biogas domestic supply per continent for 2017.

Bioenergy

- Low density and high initial cost in bioenergy
- Biofuels contribute to air pollution with carbon monoxide, dioxide, particulate matter
- Advantage of transport and storage with the use of biofuels
- Main resource for domestic use in developing countries

- In this chapter, an overview of energy use was presented. The use of fossil fuels and their impact was discussed. Renewable energy was introduced and a description of solar energy, wind energy and bioenergy was presented, based on their characteristics, operation and worldwide status.

Summary

Introduction and Overview of Renewable Energy Resources (RESs) (1/2)

Thank You

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Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

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Introduction to Renewable Energy

Lecture 2: Introduction and Overview of Renewable Energy Resources (RESs) (2/2)

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Section Outline

In this section, the rest of renewable energy types are introduced, geothermal, hydropower and marine energy, along with their characteristics and operation principles. The basic storage devices are described and renewable energy aspects and issues are discussed.

Section 1

Introduction to Renewable Energy

This week's topics…

- Geothermal Energy
- Hydropower
- Marine Energy
- Storage
- Renewable Energy Issues and Aspects

Geothermal Energy

- Geothermal energy is the heat from the subsurface of Earth, from the planet's formation and radioactive decay of material
- Melting rock moves from the mantle to the crust, along the edges of tectonic plates
- Temperature increases with depth
- Formation of hot springs, geysers, fumaroles, mud pots

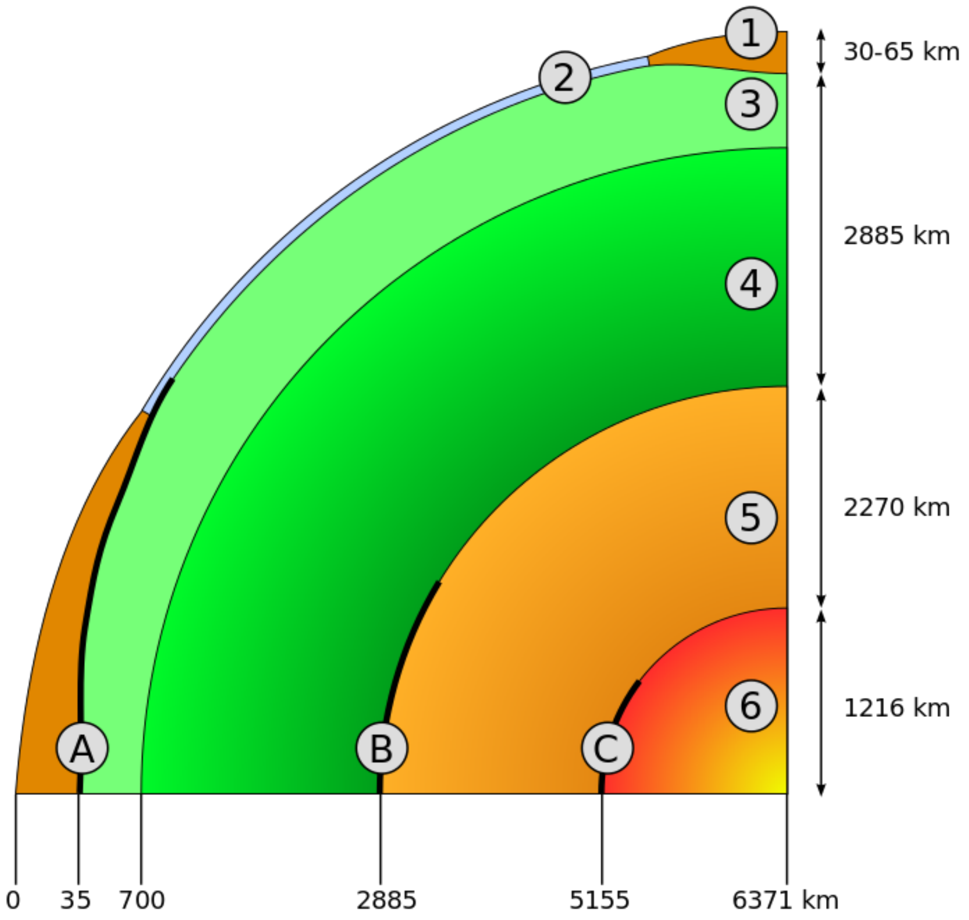


Figure 2-1: Earth's inner structure. (1.continental crust, 2.oceanic crust, 3.upper mantle, 4.lower mantle, 5.outer core, 6.inner core, A.crust-mantle boundary, B.core-mantle boundary, C.inner-outer core boundary).

Geothermal Energy

- Average increase in temperature with depth is 25-30 °C/km
- Mean heat flow to Earth's surface is 60-65 mW/m^2, higher in geothermal reservoirs
- Geothermal resources around the boundaries of tectonic plates
- E.g. Ring of Fire around Pacific Ocean, Hawaii, Yellowstone National Park, Iceland etc.

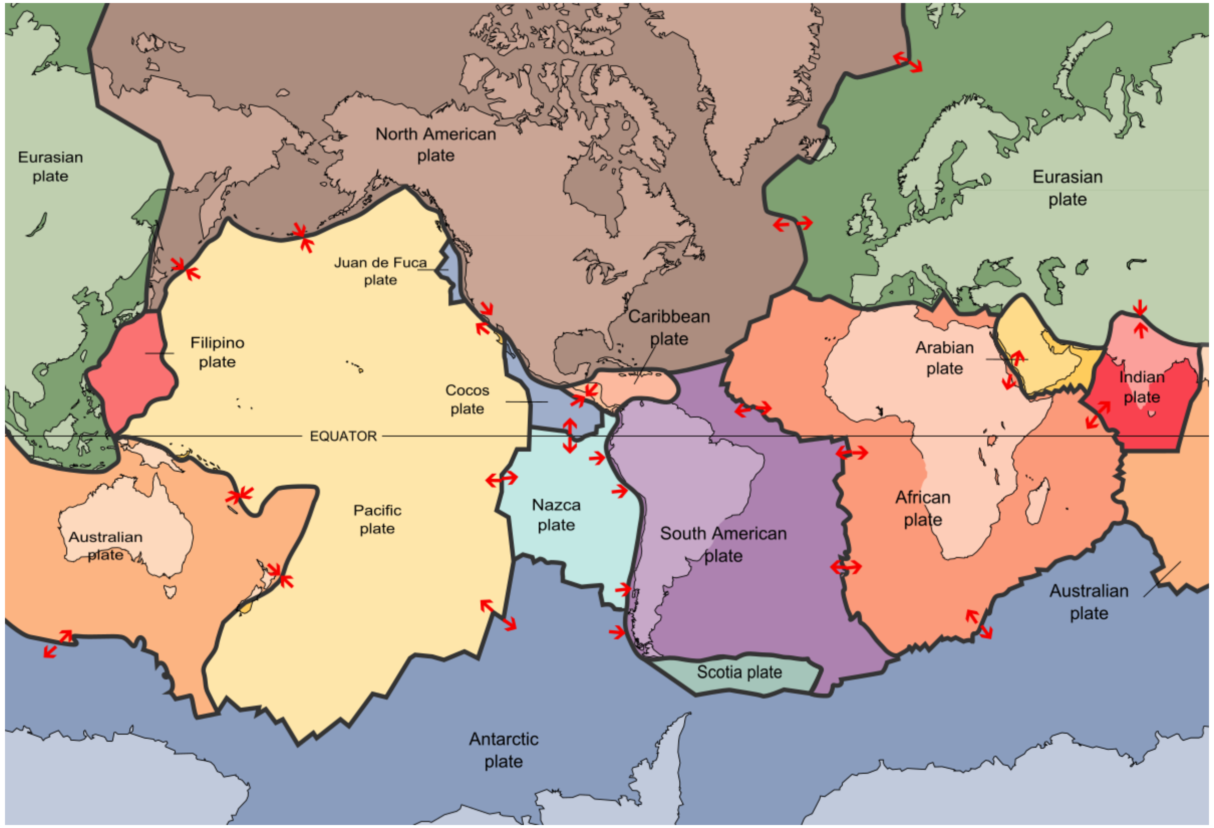


Figure 2-2: Earth's largest tectonic plates.

Geothermal Energy

Figure 2-3: The Strokkur geyser in Iceland.

Figure 2-4: The Grand Prismatic Spring, a hot spring in Yellowstone National Park, USA.

Geothermal Energy

Figure 2-5: Mud pots at Hveraröndin Iceland.

Figure 2-6: A fumarole at Námafjall, Iceland.

Geothermal Energy

- Hot springs and thermal pools used since pre-historic times, for bathing, healing
- Space heating in Roman times
- Geothermal energy now also used for electricity production
- Available in limited locations
- Small portion is being exploited, majority of geothermal resources deep in Earth’s crust, where it’s difficult and expensive to reach and use

Geothermal Energy

- Heat content of a geothermal reservoir depends on pressure, temperature, volume
- High temperature, water and steam >150°C
- Medium temperature, water and steam between 100°C and 150°C
- Low temperature, water <100°C, no steam
- Low temperature reservoirs at low depths used for space heating, greenhouses, spas etc.
- High temperature reservoirs accessible with drilling, used for electricity production

Geothermal Energy

- Heat is extracted with systems like heat pumps or enhanced geothermal systems

- USA, Indonesia, Philippines top in installed capacity, located in the Ring of Fire

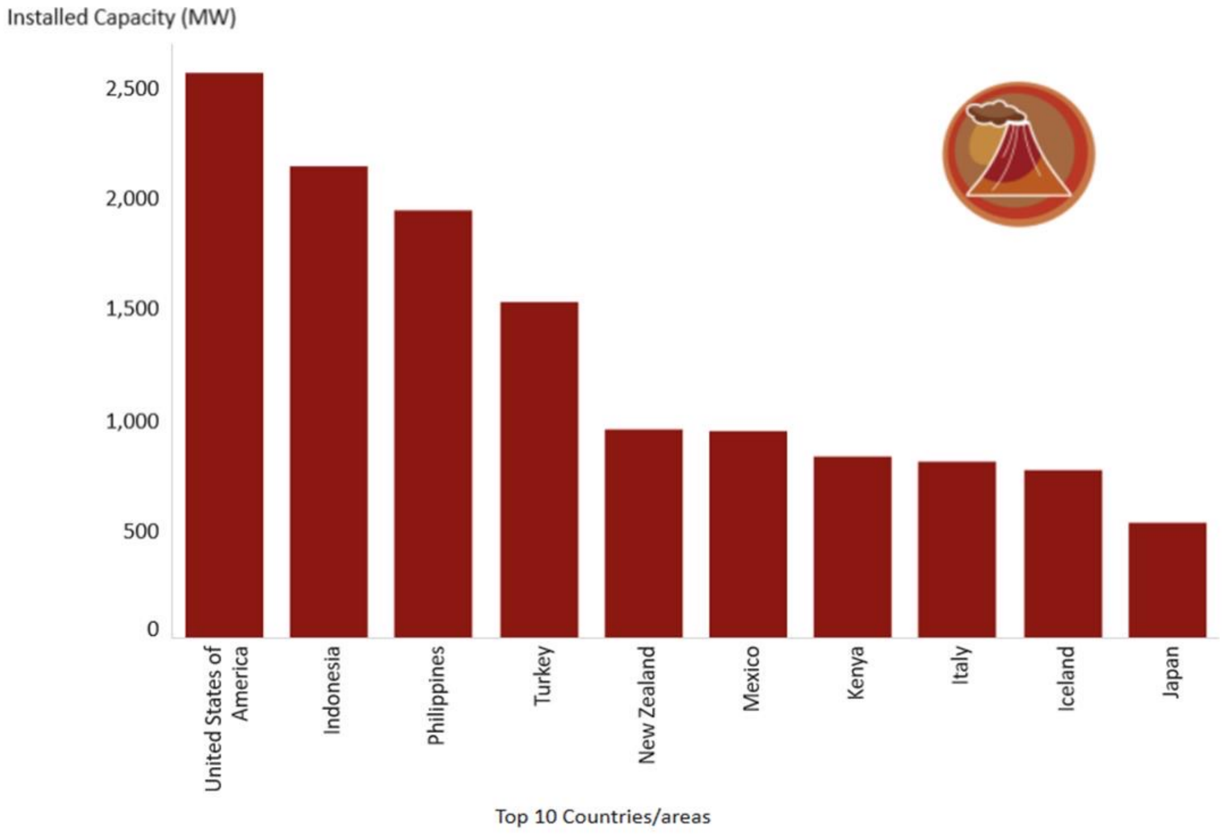


Figure 2-7: Installed capacity for geothermal energy, for the top 10 countries, in 2019.

Geothermal Energy

Geothermal Resources

Hydrothermal Convection

- Most common geothermal reservoirs are liquid-dominated, water temperatures >200°C
- Water boils to form steam in vapor-dominated systems with temperatures up to 300°C
- Both are hydrothermal convection systems, permit convection and have fractures to allow recharge
- Examples: hot springs, geysers

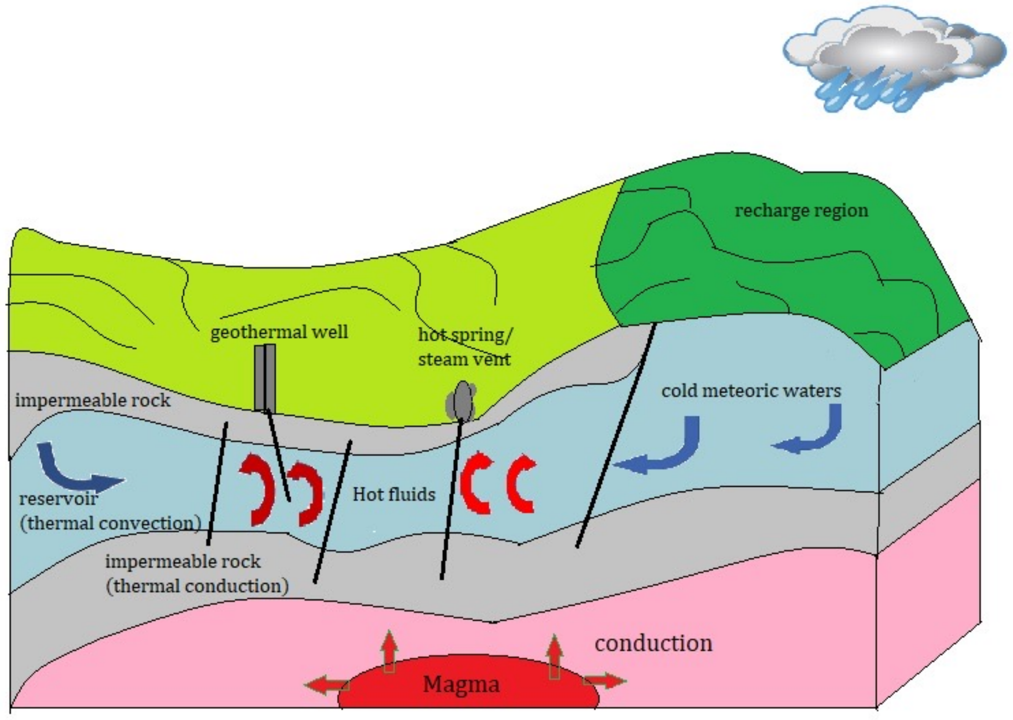


Figure 2-8: Schematic of a geothermal system.

Geothermal Energy

Geothermal Resources

- Hot igneous resources: include hot dry rock and geologic magma systems

- Conduction-dominated resources: include sedimentary basin, geopressured, radiogenic resources

Geothermal Energy

Geothermal Resources

Conduction-dominated

- Sedimentary basins have high heat flow, fracture is required, deep drilling
- Geopressured resources are in deep basins, fluids within permeable sedimentary rocks are heated due to high depth
- Radiogenic resources are in sites with granite intrusion near the surface, heating of groundwater due to radioactive decay of uranium, potassium and thorium

Geothermal Energy

Geothermal Resources

Hot igneous

- Hot dry rock systems have temperatures up to 350 °C
- Heat is stored in rocks deep in the ground
- Energy extraction is not possible through natural water or steam flow
- Enhanced geothermal systems (EGS) are used
- Magma resources up to 1400 °C
- Experimental systems are designed to extract heat from molten rock

Geothermal Energy

Geothermal Resources

- Shallow and intermediate hydrothermal systems used for direct heating, power generation
- Shallow systems at normal temperatures, used for direct heating and cooling with heat pumps
- Deep systems for power production with EGS
- Dashed line refers to intermediate systems at normal temperatures, can be used in the future for power production

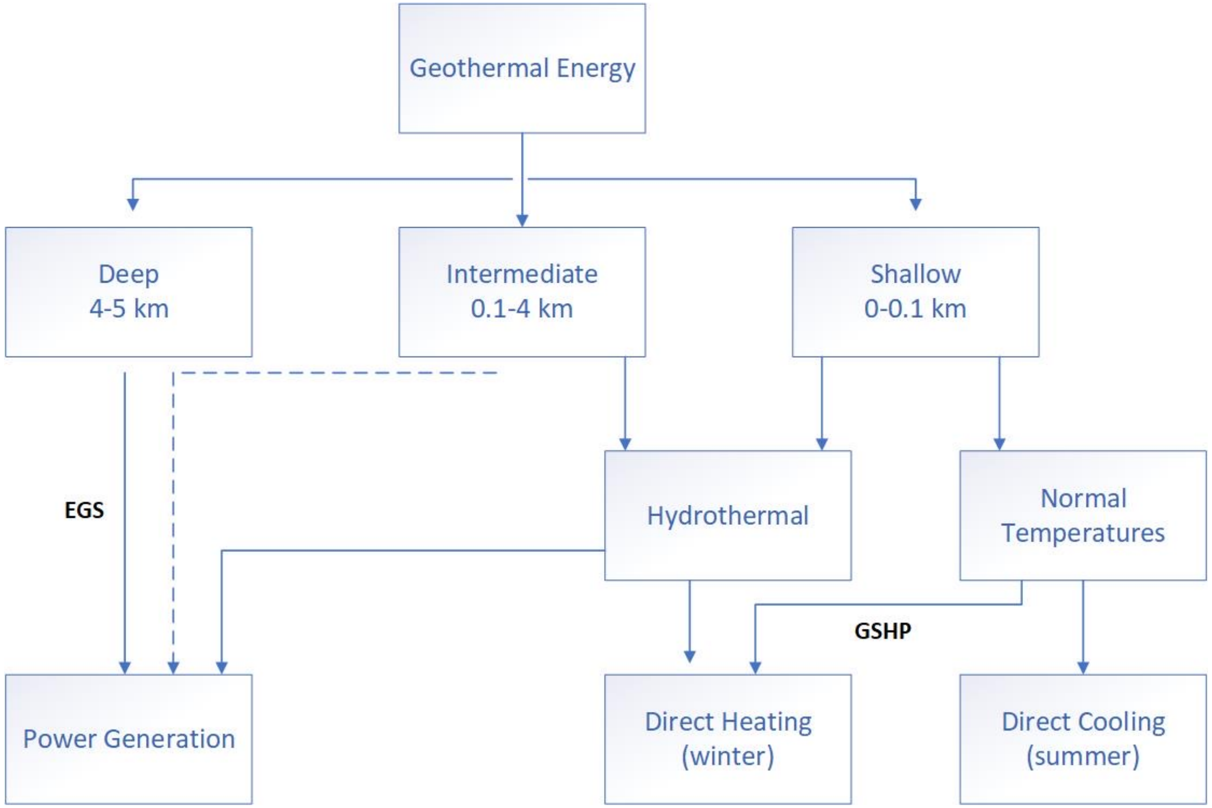


Figure 2-9: Forms of geothermal energy and utilization depending on depth.

Geothermal Energy

Enhanced Geothermal Systems

- ○ EGS systems used in hot dry rock resources for electricity generation, with stimulation methods like hydraulic stimulation
- ○ High-pressure cold water pumped down an injection well to enhance the permeability of rock
- ○ Fluid pressure increases
- ○ Second borehole made for the heated water in the rock to be forced out

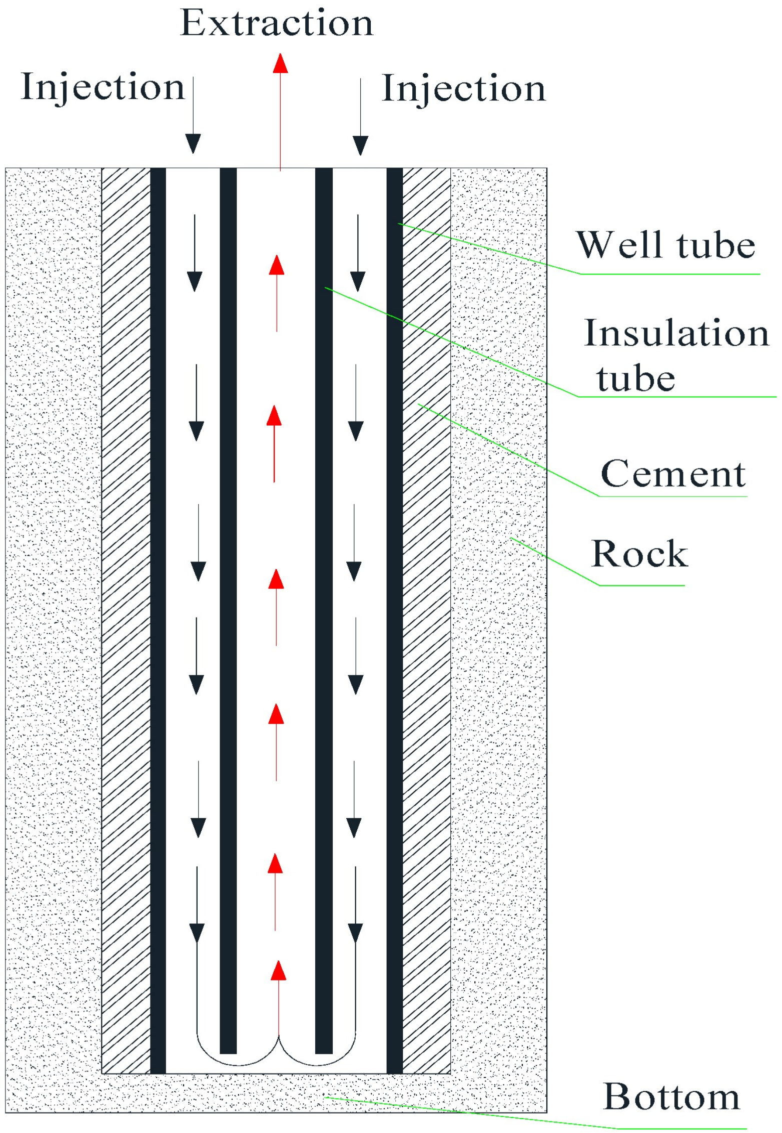


Figure 2-10: Schematic of an Enhanced Geothermal System.

Geothermal Energy

Enhanced Geothermal Systems

- Heat from water can be converted to electricity in a steam turbine or power plant
- High production rate must be achieved without rapid cooling of the reservoir, which will reduce its lifetime
- Risks of induced seismicity
- No commercial EGS systems, designs are made for testing

Geothermal Energy

Geothermal Heat Pumps

- A geothermal heat pump (GHP) is a central heating/cooling system
- Transfers heat from/to the ground for space heating/cooling
- A circulating fluid is transferred through pipes, built in boreholes or trenches and a pump extracts heat to the surface
- The cool circulated fluid is injected back into the ground

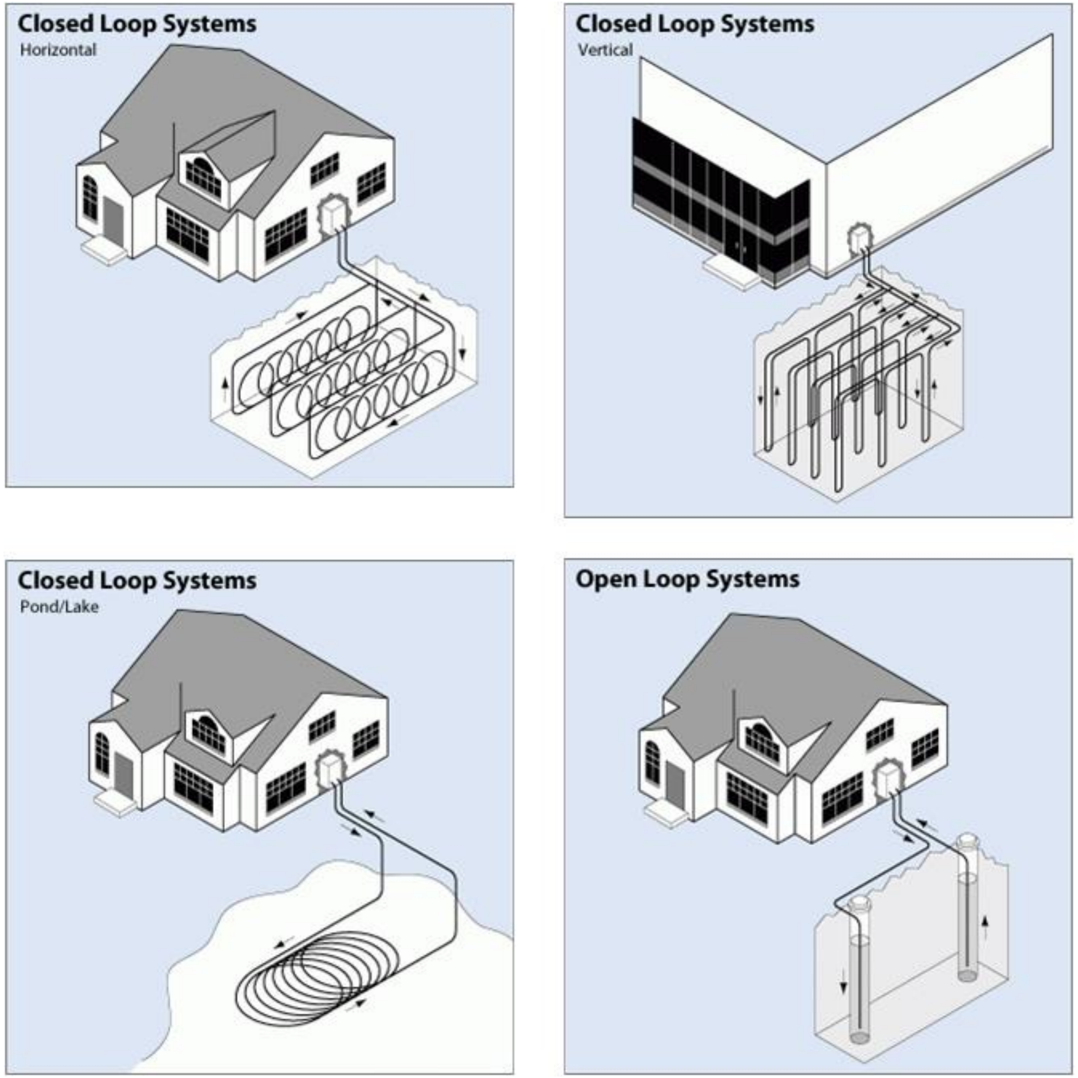


Figure 2-11: Examples of various types of geothermal heat pumps.

Geothermal Energy

Geothermal Heat Pumps

- Operation is reversed for space cooling
- Closed-loop or open-loop system, in which wells or a surface body water is used as the heat exchange fluid
- GHP systems used 25-50% less electricity than conventional heating/cooling systems
- Use anywhere in the world
- Over a million systems in the USA, Germany the leading market in Europe

Geothermal Energy

Direct Use

- Direct uses include space heating/cooling, greenhouses, fish farming, bathing, swimming, health spas
- Spas, bathing use heat from hot springs, no pumps required
- Pumps are applied to other systems to transfer hot water to surface
- Top 5 countries in direct use installed capacity (including geothermal heat pumps): China 40.6 MWt, USA 20.7 MWt, Sweden 6.7 MWt, Germany 4.8 MWt, Turkey 3.5 MWt
- In terms of population, Iceland in the first place

Geothermal Energy

Direct Use

- Geothermal heat pumps highest use worldwide
- Large increase during the last years
- Direct use exploits both high and low temperature reservoirs, thus more common than electricity production installations
- Direct use can only be applied near the reservoir

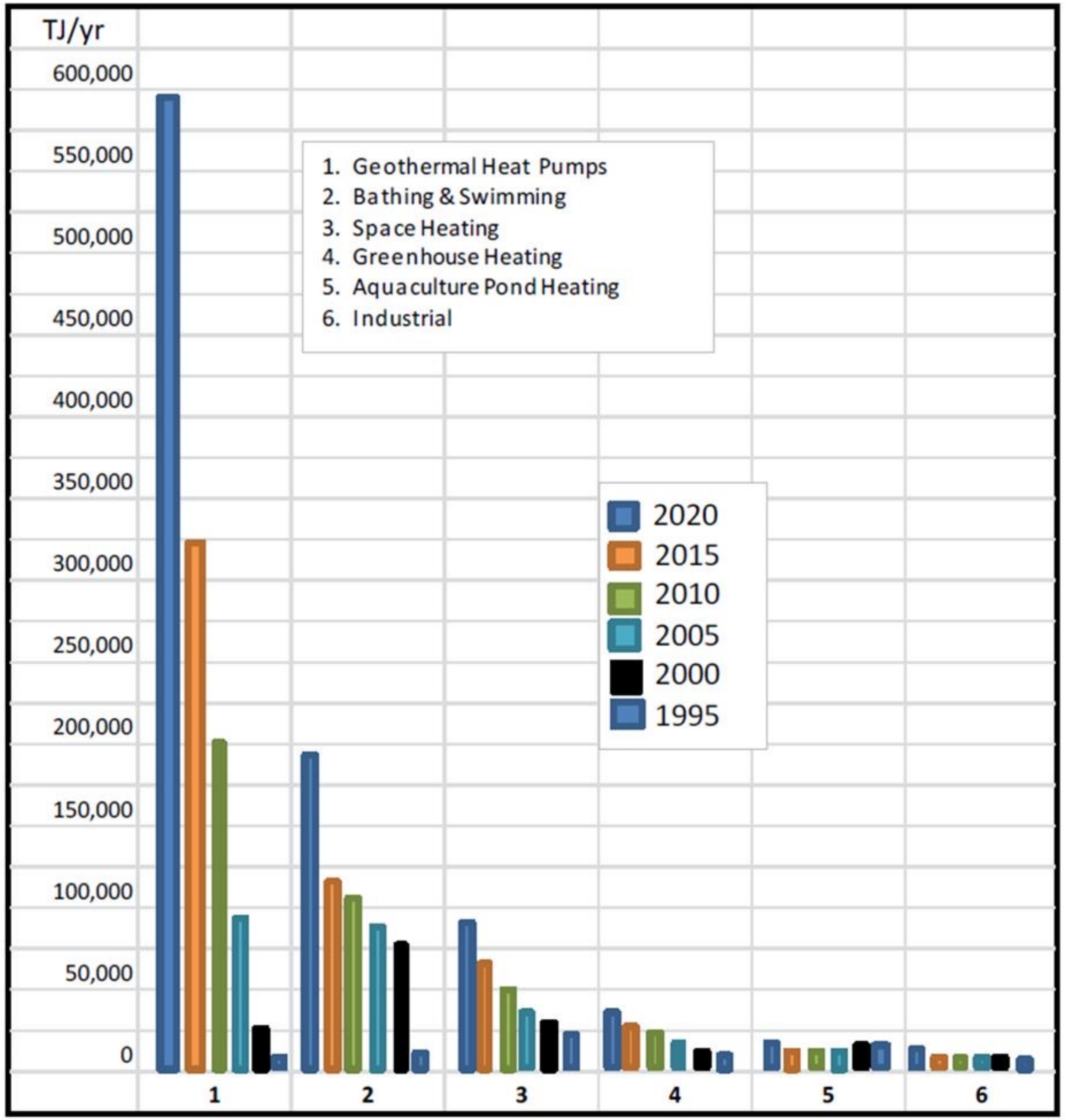


Figure 2-12: Worldwide direct use of geothermal energy (TJ/year) from 1995 to 2020 per category.

Geothermal Energy

Direct Use

District Heating

- District heating is a system for heat distribution for residential, commercial purposes, with direct use of geothermal energy
- First system in 1892 in Boise, Idaho, USA
- Turkey uses 493 MWt for district heating
- Largest district heating system in Reykjavik, Iceland, geothermal energy from several high and low temperature reservoirs, inside and near the city
- 780 MWt to heat whole city and five communities nearby

Geothermal Energy

Electricity Generation

- Electricity generation from geothermal energy:
  - *Dry steam*
  - *Flash steam*
  - *Binary cycle power stations*

- Medium and high temperature reservoirs are required
- In 2015, global geothermal power capacity was 12.8 MW, most of which in USA

Geothermal Energy

Electricity Generation

- Dry steam is the oldest, simplest type
- Steam from a reservoir (≥150 °C) is routed through a turbine/generator
- Steam is then lead to a condenser, turns liquid and cools down
- Lead back to the well to be reheated
- Largest dry steam facility is the Geysers, California, 13 dry steam power plants with net capacity of 725 MW

Dry Steam

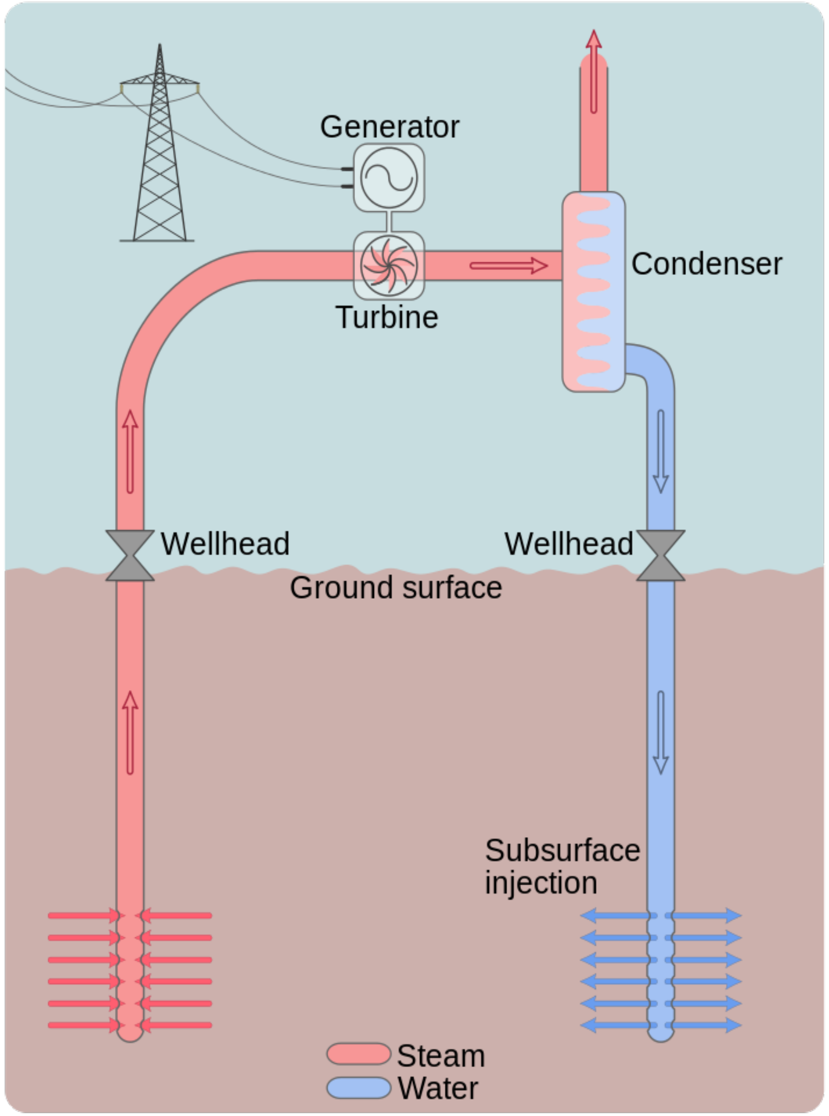


Figure 2-13: Schematic of a dry steam power station.

Geothermal Energy

Electricity Generation

- Flash steam is the most common today
- Water is used from high temperature reservoirs, (≥180 °C)
- High-pressure water enters a lower pressure tank and flashed steam is formed to drive a turbine
- Remaining water and condensed steam are pumped back into the ground
- CalEnergy Navy I plant at Coso geothermal field, California can produce 270 MW of electricity
- Wairakei station in New Zealand consists of a flash steam plant of 140 MW and a binary cycle plant which increased output to 181 MW

Flash Steam

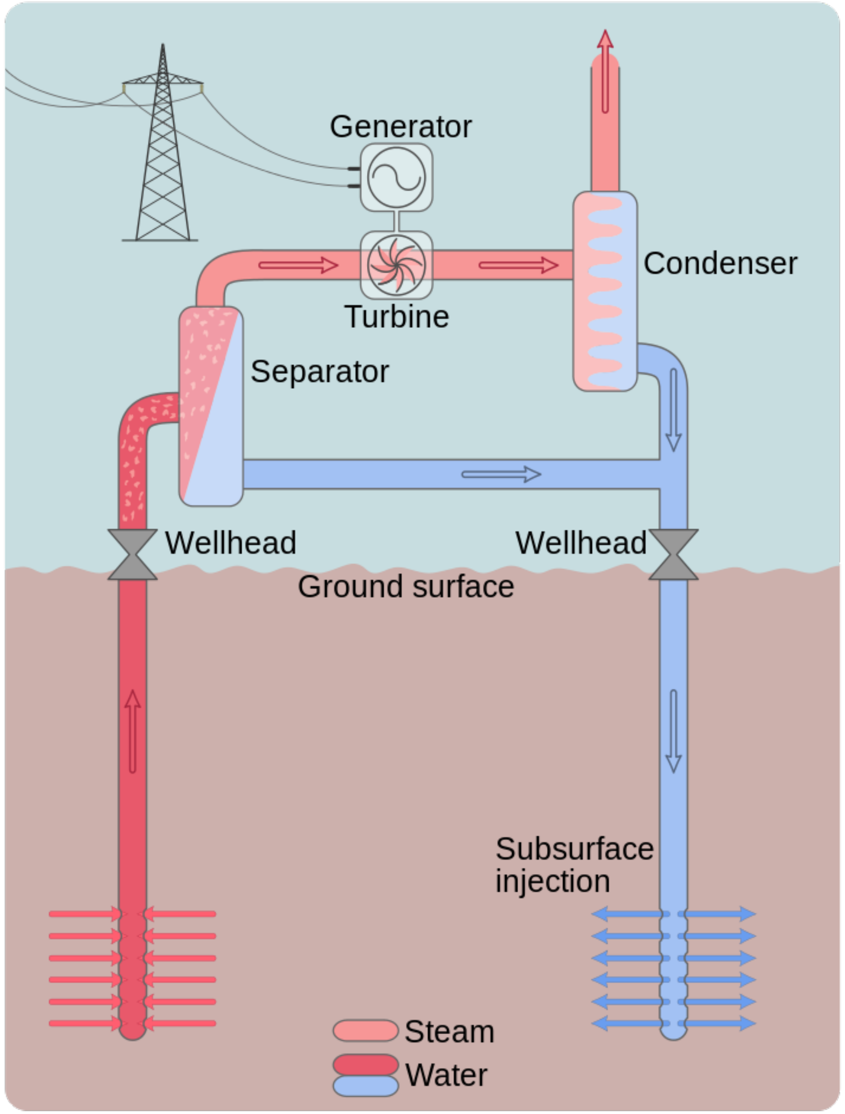


Figure 2-14: Schematic of a flash steam power station.

Geothermal Energy

Electricity Generation

- Binary cycle is the newest power plant type
- Fluid from reservoir doesn't drive the turbine directly
- Reservoir water is used to heat a second working fluid, which is vaporized and used to drive the turbine
- Second working fluid has lower boiling point than water
- Lower temperature reservoirs can be exploited
- McGinness Hills Geothermal Complex, Nevada has 3 binary cycle plants and total capacity of 138 MW

Binary Cycle

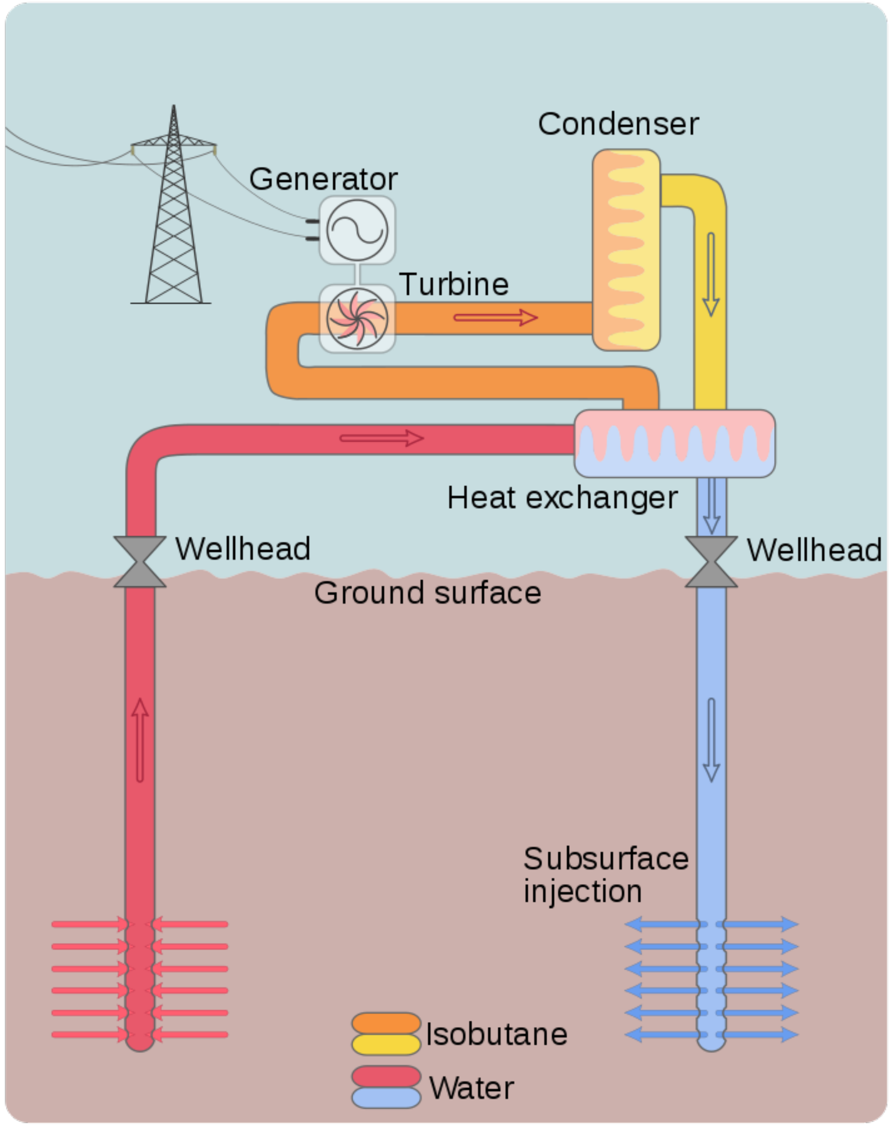


Figure 2-15: Schematic of a binary cycle power station.

Geothermal Energy

- Geothermal energy is a renewable resource since the amount exploited is very small compared to Earth’s total thermal content
- Uncontrolled exploitation however could lead to depletion of local resources
- Exploitation releases mixture of gases, some contributing to global warming, but emissions are less than those from fossil fuels
- Other toxic elements may be released from the hot water, such as mercury or arsenic

Geothermal Energy

- Return of working fluids into the ground minimizes risks of contamination and depletion
- Effects on land stability is an important issue
- Land subsidence or uplift has been observed in areas of geothermal power plants
- Risks of triggering earthquakes due to deep drilling of enhanced geothermal systems

Hydropower

- Hydropower is derived from the energy of moving water
- In use since ancient times, e.g. watermills for irrigation and operation of mechanical devices
- Watermills are still in use for grinding grain, e.g. Himalayas or elevated regions in developing countries
- Late 1800s water from a dam was first used to generate electricity
- First hydroelectric plant in 1879, Niagara Falls, USA

Hydropower

- Water has potential energy due to height difference

$PE = F * d = m * g * H, \quad J$ F force due to gravity, d distance, m mass of water, g acceleration of gravity, H height. Since $m=\rho V$ and $\rho=1000 kg/m^3$ for water

$$PE = 10000 * V * H, \quad J$$

Potential energy is converted to kinetic energy as water falls $KE = PE$

$$0.5 * m * v^2 = m * g * H$$

$$v = (2 * g * H)^{0.5}$$

Energy/time gives the power, while V/time gives the water flow and as ε is the efficiency of the turbine, the power is calculated

$$P = 10000 * \varepsilon * Q * H = 10 * \varepsilon * Q * H, \quad kW$$

- Water flow data important for hydropower installations

Hydropower

Hydropower Resources

- Hydropower relies on water cycle
- Solar energy heats surface water which evaporates
- Vapors condense in the atmosphere and return as precipitation
- The flow of water which is collected back to rivers and streams is the source for hydropower production
- In 2018 global electricity production from hydropower (pumped storage not included) reached 4150 TWh

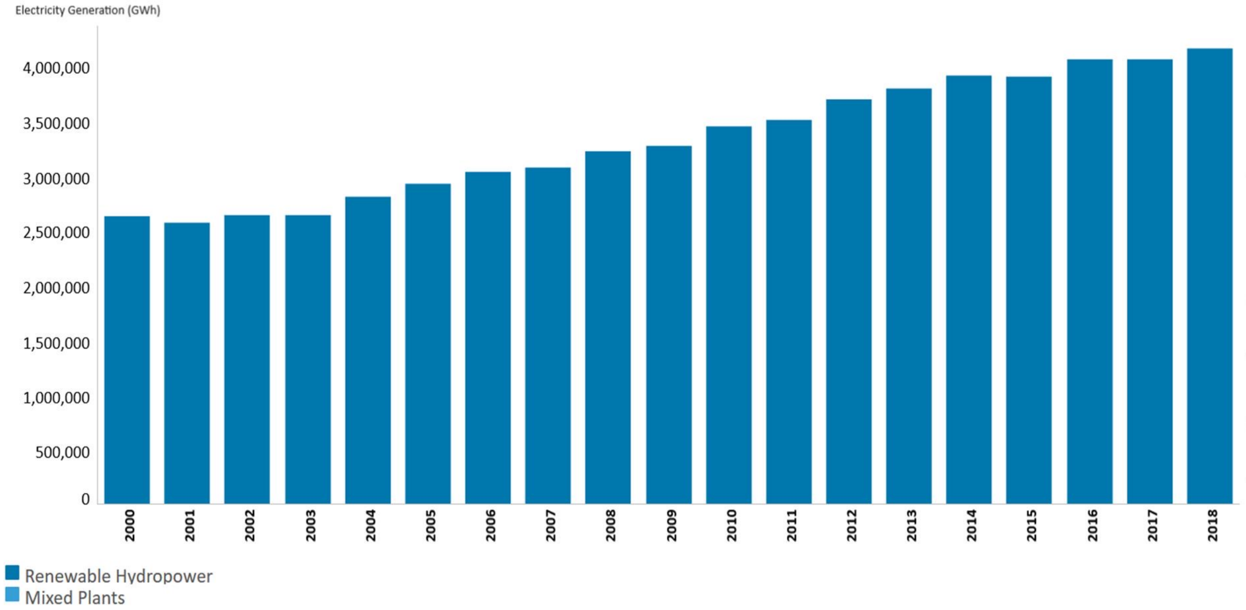


Figure 2-16: Total electricity generation (GWh) from hydropower, excluding pumped storage.

Hydropower

Hydropower Resources

- Hydropower is the largest source of global renewable electricity generation, 65% in 2017
- Can be used for production of mechanical power, like in water mills, where a water wheel or turbine is used for grinding or hammering etc., or in trompes, which are water-powered air compressors
- Main use is the production of electricity
- Low cost, site specific

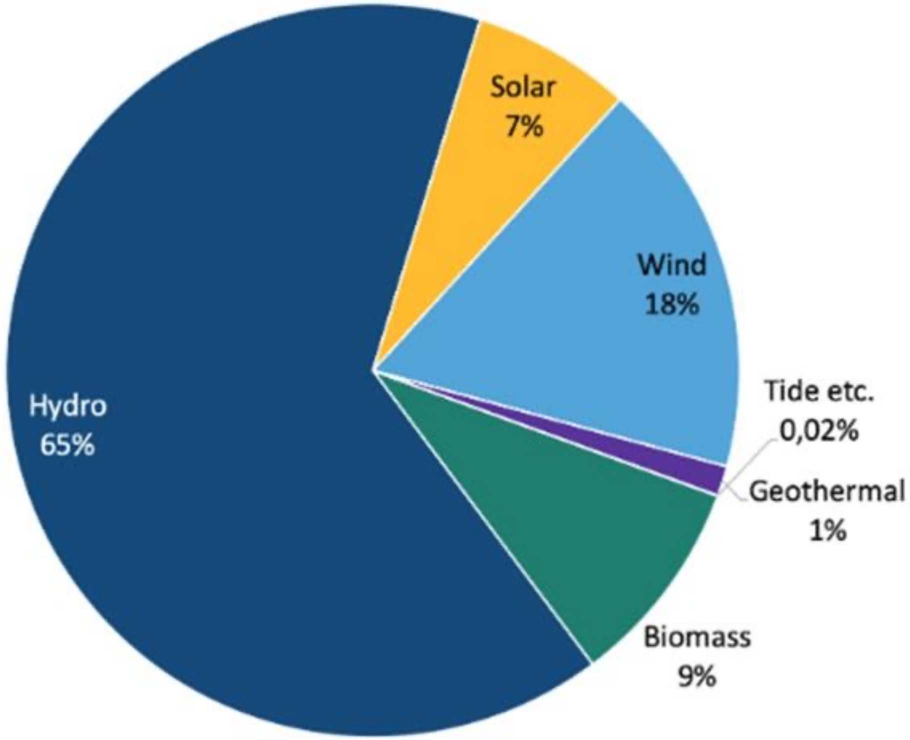


Figure 2-17: Electricity production from renewable resources for 2017.

Hydropower

Types of Hydropower

- Hydropower is classified according to power output:

  large-scale, small, micro, pico

- Large-scale produces more than a few hundred MW, largest plants reach capacity of thousands MW
- China lead country, largest plant is the Three Gorges Dam, 22.5 GW
- Second largest is the Itaipu Dam, Brazil-Paraguay, 14 GW
- Xiluodu Dam, China, 13.8 GW, Guri Dam, Venezuela, 10.2 GW

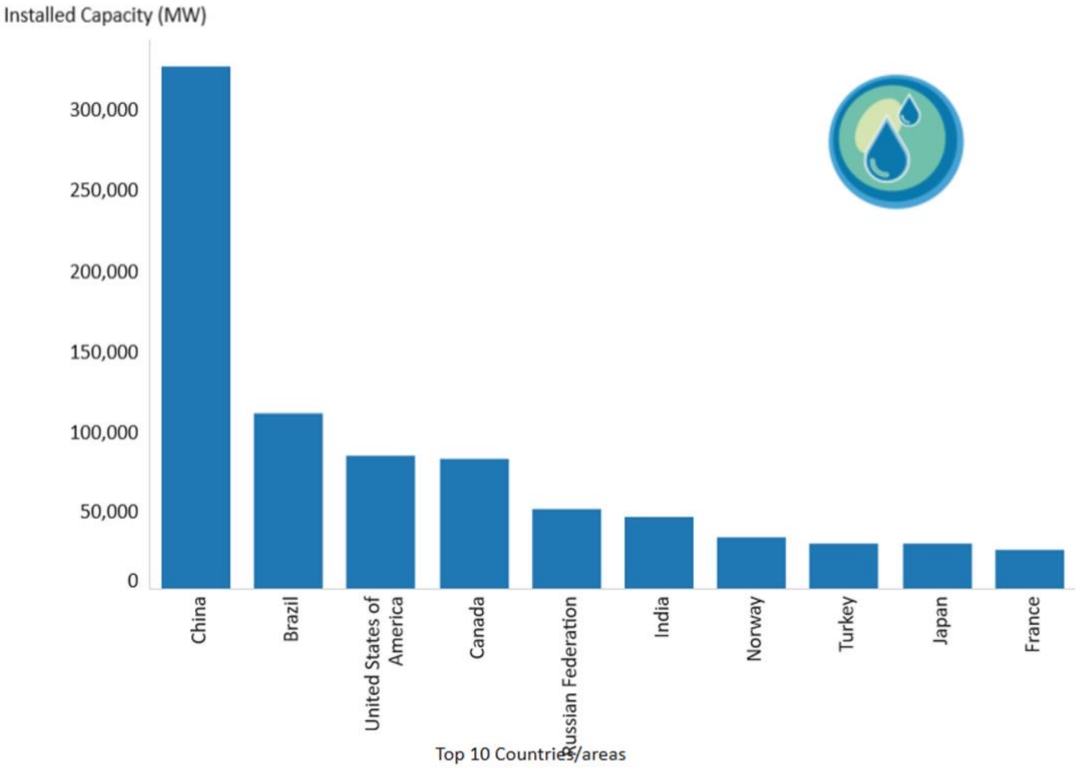


Figure 2-18: Installed capacity of hydropower (MW) exc. pumped storage, for the top 10 countries, for 2019.

Hydropower

Types of Hydropower

- Small hydropower, up to 10 MW (25-30 MW in USA, Canada)
- Small hydropower can be connected to distribution network or work alone in remote areas

Figure 2-19: The Three Gorges Dam in China.

Hydropower

Types of Hydropower

- Micro hydro, <100 kW, can power a home or small community, or even connect to local network
- Micro hydro installations in developing countries, no need for dams or reservoirs
- Pico hydro, <5 kW, power a few devices, don’t require dams only pipes to divert water flow

Hydropower

Hydroelectric Stations

- Hydropower facilities are categorized into three types:
  - *Impoundment (dam)*
  - *Diversion (run-of-the-river)*
  - *Pumped storage*

Hydropower

Hydroelectric Stations

Impoundment (dam)

- Impoundment is the conventional dam hydropower plant
- A dam is used to store water from a river in a reservoir
- Water is released from elevated position to drive a turbine
- A generator is activated to produce electricity
- Power depends on water volume and the head (height difference between water level at the reservoir and the tailwater level, downstream)

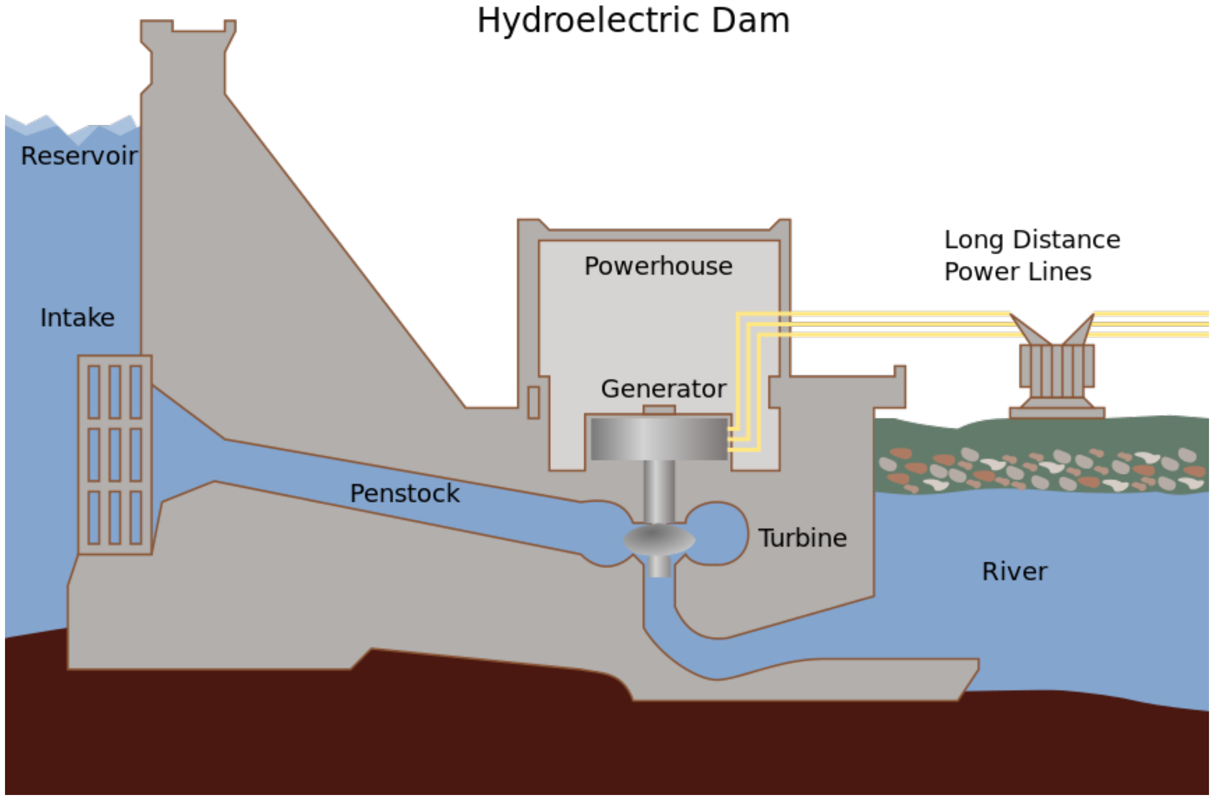


Figure 2-20: A conventional hydropower plant.

Hydropower

Hydroelectric Stations

- Penstock is the pipe through which water is driven from the reservoir to the turbine
- Water can be released to meet electricity demands or maintain certain level in the reservoir
- Hoover Dam in Nevada/Arizona, USA has a capacity of 2080 MW

Impoundment (dam)

Figure 2-21: Hoover Dam in Nevada/Arizona, USA.

Hydropower

Hydroelectric Stations

Pumped Storage

- In pumped storage, water is pumped uphill, from a low elevation to a higher elevation reservoir
- Energy storage for later use
- When demanded, water is released back to lower reservoir to drive a turbine
- One route for pumping water and storing energy, other route for generating electricity

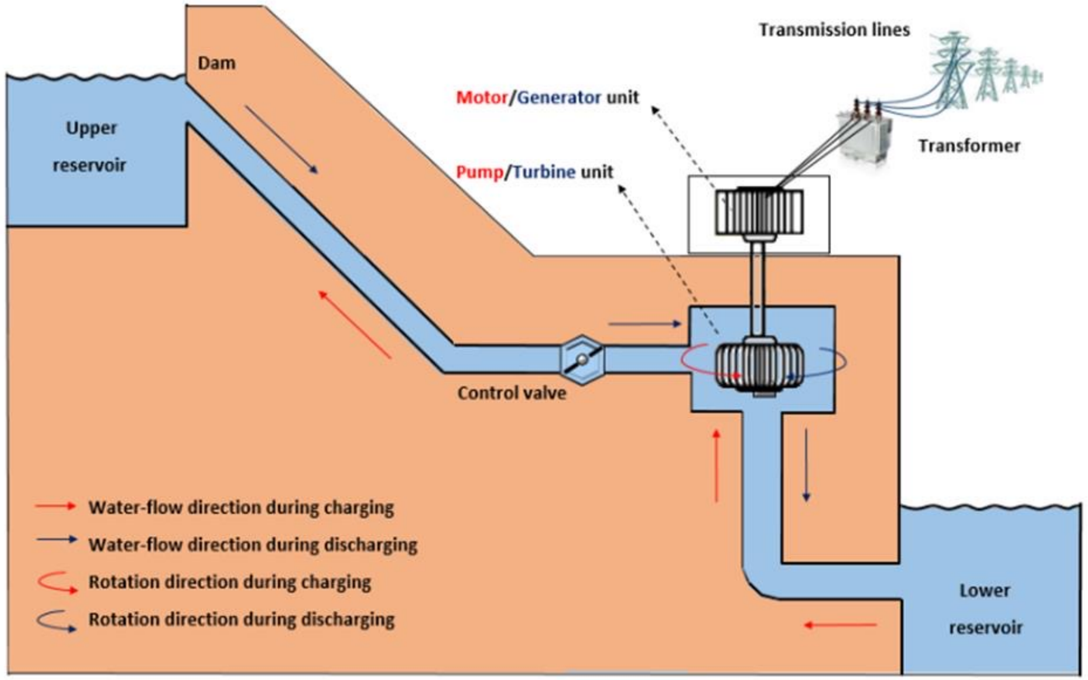


Figure 2-22: Pumped storage hydropower plant.

Hydropower

Hydroelectric Stations

Pumped Storage

- Pumped storage facilities have the role of a battery
- Most important means of energy storage
- Castaic Pumped Storage Plant, USA has a capacity of 1250 MW

Figure 2-23: The Castaic Pumped Storage Plant, USA.

Hydropower

Hydroelectric Stations

Diversion (run-of-the-river)

- Diversion or run-of-the-river are facilities with small or no reservoir
- Water from a river is channeled through a canal or a penstock to drive a turbine
- Limited flexibility to follow peak variation in electricity demand
- Mainly used for baseload capacity

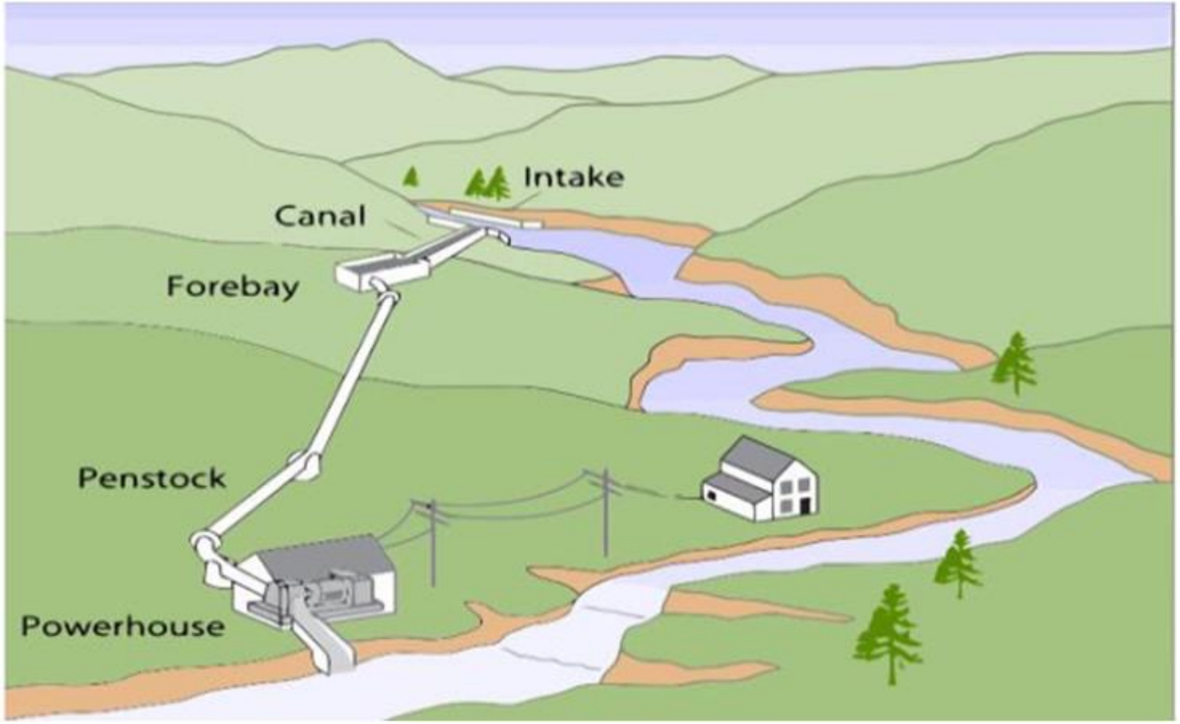


Figure 2-24: Run-of-the-river hydropower plant.

Hydropower

Hydroelectric Stations

Diversion (run-of-the-river)

- May have small storage reservoir (pondage) to meet daily demands
- These facilities divert part or most of the river flow and lead it through a pipe to the turbine and then back to the river downstream
- Chief Joseph Dam in Washington, USA has a capacity of 2620 MW

Figure 2-25: Chief Joseph Dam, a run-of-the-river plant in Washington, USA.

Hydropower

Water Turbines

- Water turbines in hydropower plants convert the potential and kinetic energy of water to electricity
- Two main types: impulse and reaction turbines
- Type selected for each power plant depends on the head and water flow
- Cost and efficiency factors to be considered

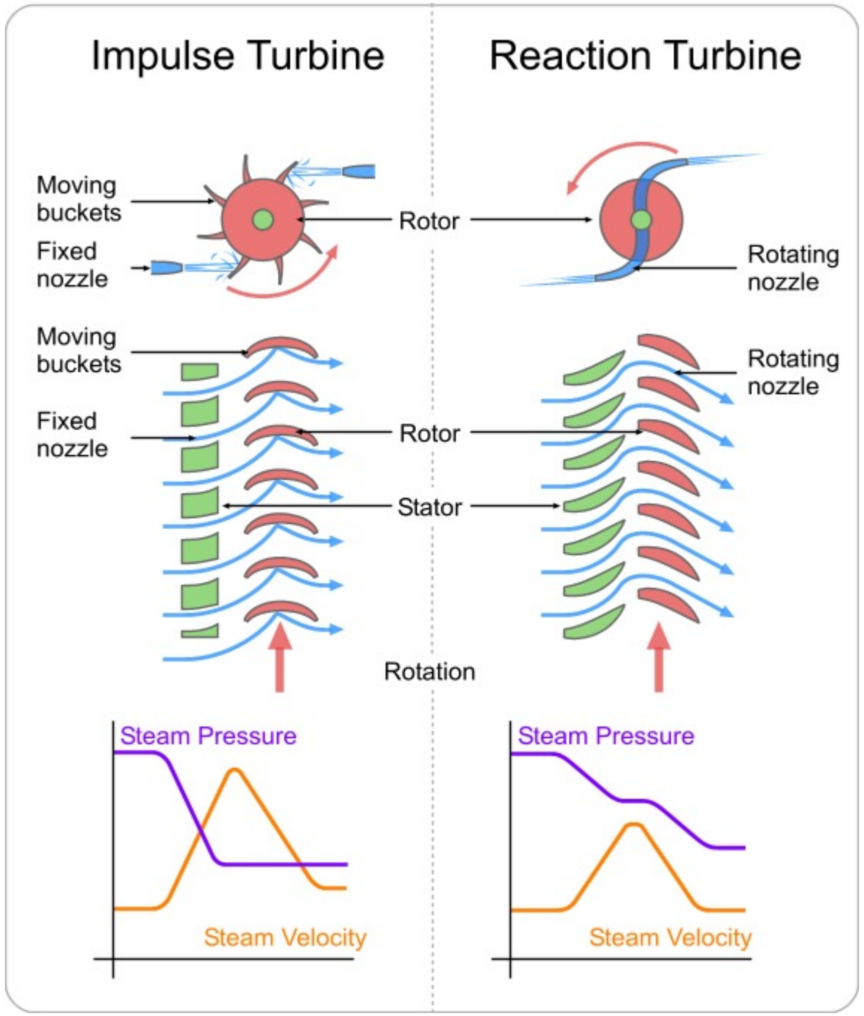


Figure 2-26: Difference between an impulse and a reaction turbine.

Hydropower

Water Turbines

Impulse turbines

- In an impulse turbine, blades spin due to fast moving water fired through a nozzle
- Blades have bucket shape to catch the water and change flow direction
- Potential energy is converted to kinetic before heating the blades
- Newton’s second law describes energy transfer
- Impulse turbines used for high head and low flow applications

Hydropower

Water Turbines

Impulse turbines

- An example of impulse turbines is the Pelton turbine
- One or more free water jets hit the buckets of the runner
- Pelton is considered one of the most efficient types, doesn't need to be inside pipe or housing

Figure 2-27: A Pelton turbine.

Hydropower

Water Turbines

Reaction turbines

- In a reaction turbine power is developed from the combination of pressure and moving water (kinetic energy)
- Water changes pressure at it moves through the turbine, giving up its energy
- Newton's third law describes the energy transfer
- Need housing to contain water pressure or be fully submerged
- Used for lower head and higher flow

Hydropower

Water Turbines

Reaction turbines

- An example of reaction turbines is the Francis turbine
- Inward flow turbine with a combination of radial and axis components
- Consists of spiral casing with openings to allow water to impinge on blades
- Pressure is converted to kinetic energy before water hits the blades
- Other components are the guide and stay vanes, runner blades, draft tube
- Usually operates in water head between 40 and 600m

Figure 2-28: A Francis turbine connected to a generator.

Hydropower

Advantages and disadvantages

- Flexibility, increases and decreases production very quickly
- Reservoirs are power on demand, little cost for storage
- Long lifetime, up to 100 years, can be used for flood control, irrigation, recreation etc.
- Low emissions of greenhouse gases
- Landscape negative effects, submersion of land, destroy forests, marshlands
- Interruption of river flow, displacement of population and wildlife
- Damage to dams from rivers with high siltation
- Risks in case of dam collapse

Marine Energy

- ○ Marine energy/ocean power comes from various sources, like waves, currents, tides, ocean thermal energy conversion and salinity
- ○ Huge resource potential
- ○ Early stages of development, ocean power the smallest contributor of renewable resources
- ○ Total installed capacity in 2019 was 530 MW

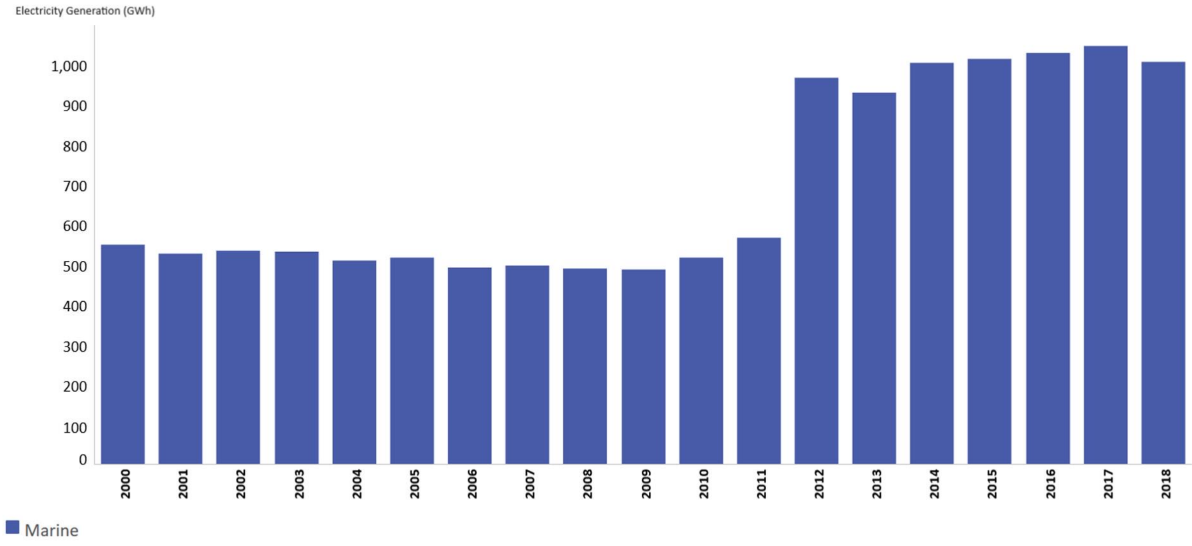


Figure 2-29: Electricity production from marine energy (GWh) from 2000 to 2018.

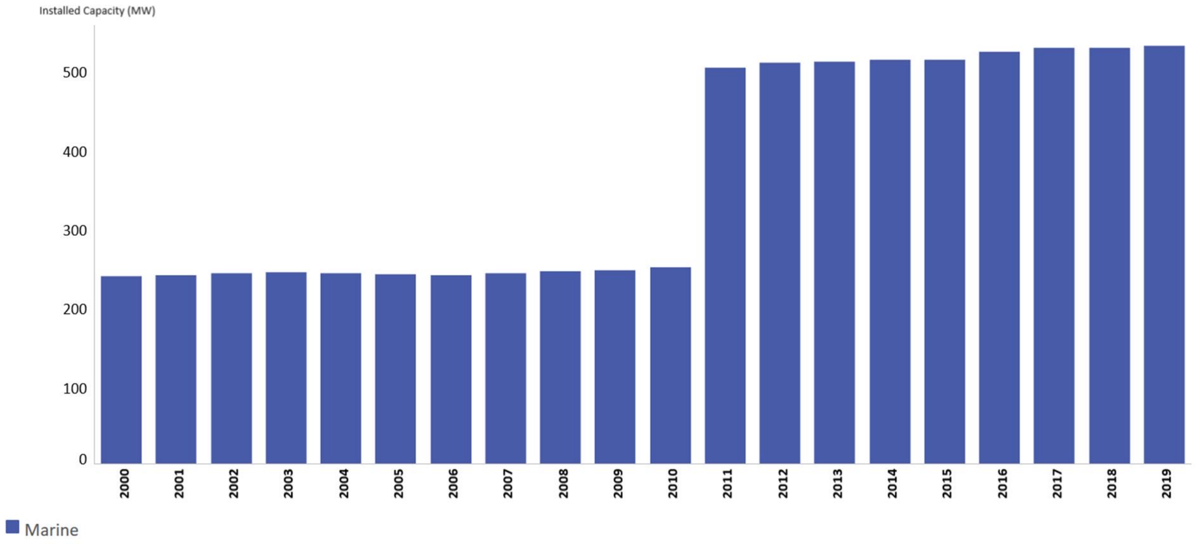


Figure 2-30: Installed capacity of marine energy (MW), from 2000 to 2019.

Marine Energy

- Republic of Korea and France amount to over 90% of total installed capacity, due to their two tidal barrages
- La Rance station in France has a capacity of 240 MW
- Sihwa power plant in the Republic of Korea has a capacity of 254 MW

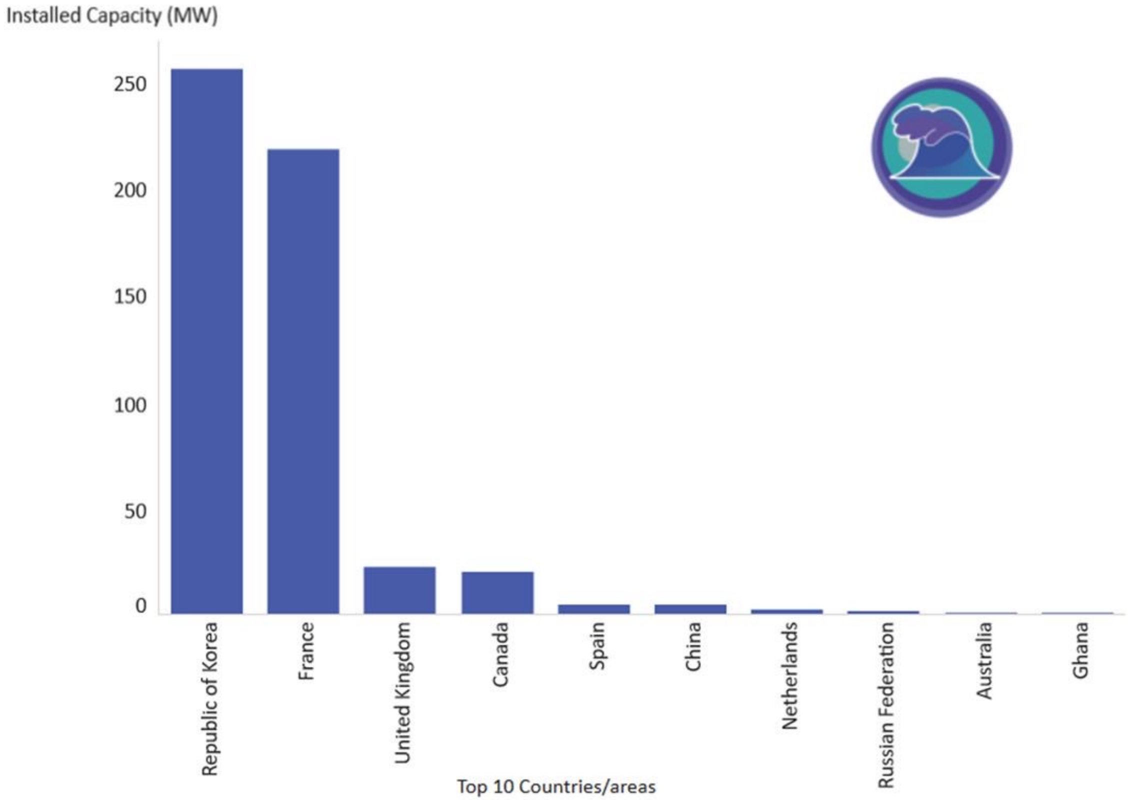


Figure 2-31: Installed capacity of marine energy (MW) for the top 10 countries, for 2019.

Marine Energy

Current Power

- Ocean currents carry large amounts of water and energy and their flow is relatively constant
- Example, the Gulf Stream transports warm water to North Atlantic
- Ocean currents are created and controlled by the wind, Coriolis effect, topography of ocean floor, temperature, salinity differences
- Ocean current power estimated around 5000 GW, with power densities up to to 15 kW/m^2

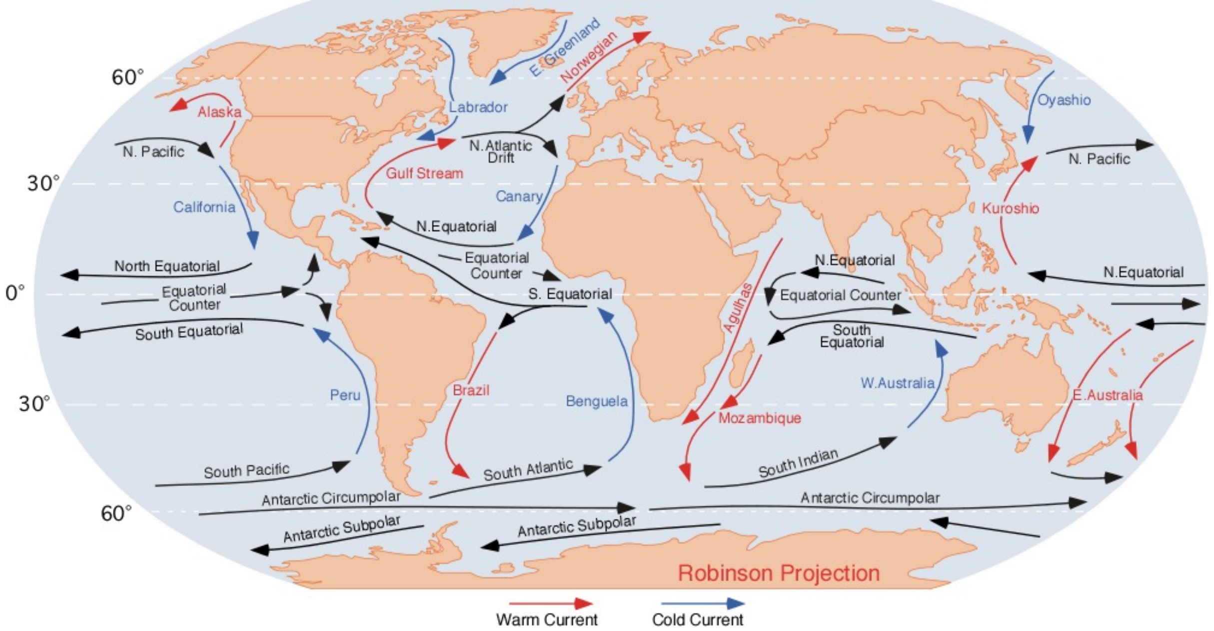


Figure 2-32: Major ocean currents worldwide.

Marine Energy

Current Power

- Advantages of current power for electricity generation: predictable resource, very large, little impact on the atmosphere
- No commercial applications though research is conducted in many countries
- Two types of turbines considered for ocean current exploitation: axial-flow horizontal-axis propellers, cross-flow Darrieus rotors
- These turbines can be supported in sea-bed mounted systems or floating moored systems

Marine Energy

Wave Power

- Waves are created from wind on ocean surface
- Energy is transferred from wind to the waves
- Waves can travel great distances without important energy loss
- Wave energy calculation, where H is the wave height

$$E = 0.5 * \rho * g * H^2/16, \qquad J$$

- Waves in the ocean are a superposition of waves

Marine Energy

Wave Power

- Wave speed in terms of its period is: speed = wavelength(λ) / period(T)
- In deep water where water depth is larger than half the wavelength, wave power per length, P/L is:

$$\frac{P}{L} = \rho * g^2 * H^2 * \frac{T}{64 * \pi} \sim 0.5 * A^2 * T, \qquad kW/m$$

- In stormy weather, large waves can have height around 15m and a period of 15sec, there is 1.7 MW of wave power across each meter of wavefront
- Wave power device captures most of that power and behind it, waves will have lower heights

Marine Energy

Wave Power

- Wave energy potential is very high worldwide due to large coastline length
- Areas with high potential are for example, west coasts of Europe and northern coast of UK, pacific coasts of North and South America, southern coasts of South Africa and Australia
- Estimations of wave power potential are provided from the National Renewable Energy Laboratory (NREL)

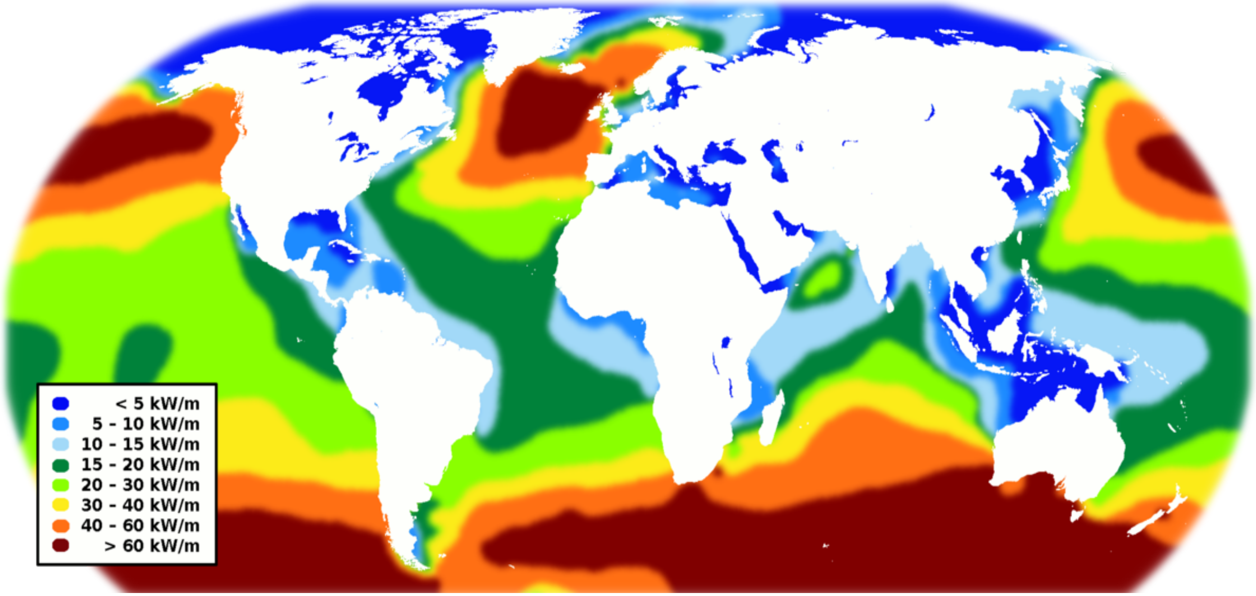


Figure 2-33: Global wave energy resources.

- For USA, estimates of 1170 TWh energy production per year

Marine Energy

Wave Power

Wave Energy Converters

- Wave energy systems can be situated on the shoreline, near the shore or offshore
- Shoreline devices are easier to install and maintain, don’t need moorings for deep waters or long cables underwater
- Shoreline devices receive less energy as wave energy decreases as it reaches the shore
- Near-shore devices are a few hundred meters away from shore, in depths 20-25m
- Wave energy resource higher for near-shore and have some advantages like shoreline devices
- Offshore devices exploit higher energy resources, depths >25m

Marine Energy

Wave Power

- Main types of wave energy converter (WEC) devices, based on the method for capturing the wave energy:
  - *Attenuator*
  - *Point absorber*
  - *Oscillating wave surge converter*
  - *Oscillating water column*
  - *Overtopping/terminator*
  - *Submerged pressure differential*
  - *Bulge wave*
  - *Rotating mass*

Marine Energy

Wave Power

- An attenuator (A) is a floating device, held by cables to the seabed. Operates parallel to wave direction. Captures energy from the relative motion of its two parts as wave passes by. Example the Pelamis Wave Converter

- A point absorber (B) is a floating device, absorbs energy from all directions through its movements near the water surface. The motion of the buoyant top relative to the base is converted to electricity.

Wave Energy Converters

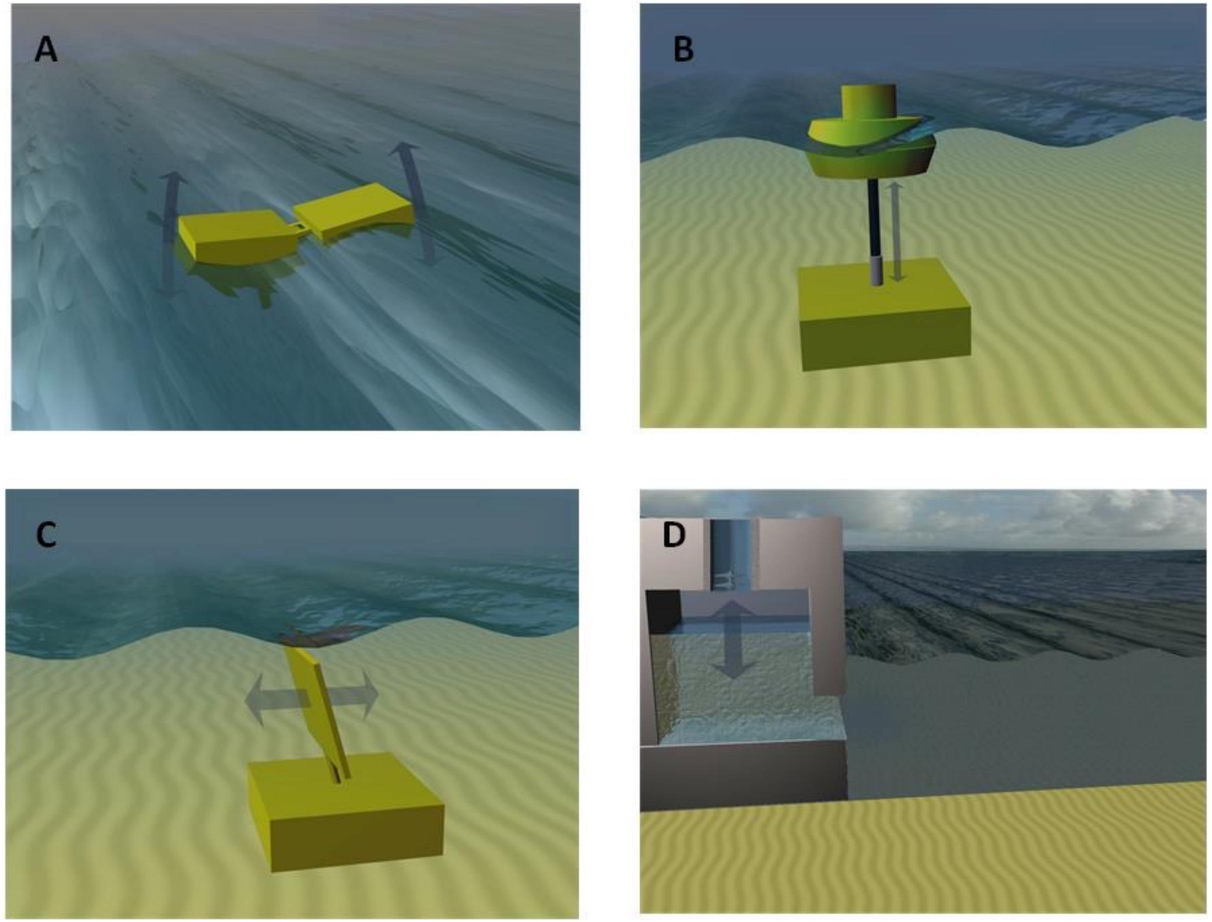


Figure 2-34: WEC devices: attenuator (A), point absorber (B), oscillating wave surge converter (C), oscillating water column (D).

Marine Energy

Wave Power

- An oscillation wave surge converter (C) uses wave surges and movement of water particles within them to extract energy. The arm of the device oscillates, in response to wave movement.

- An oscillating water column device (D) is partially submerged and hollow. Encloses a column of air on top of water column. As water column rises due to waves, the air in the column is compressed and forced through an air turbine to generate electricity

Wave Energy Converters

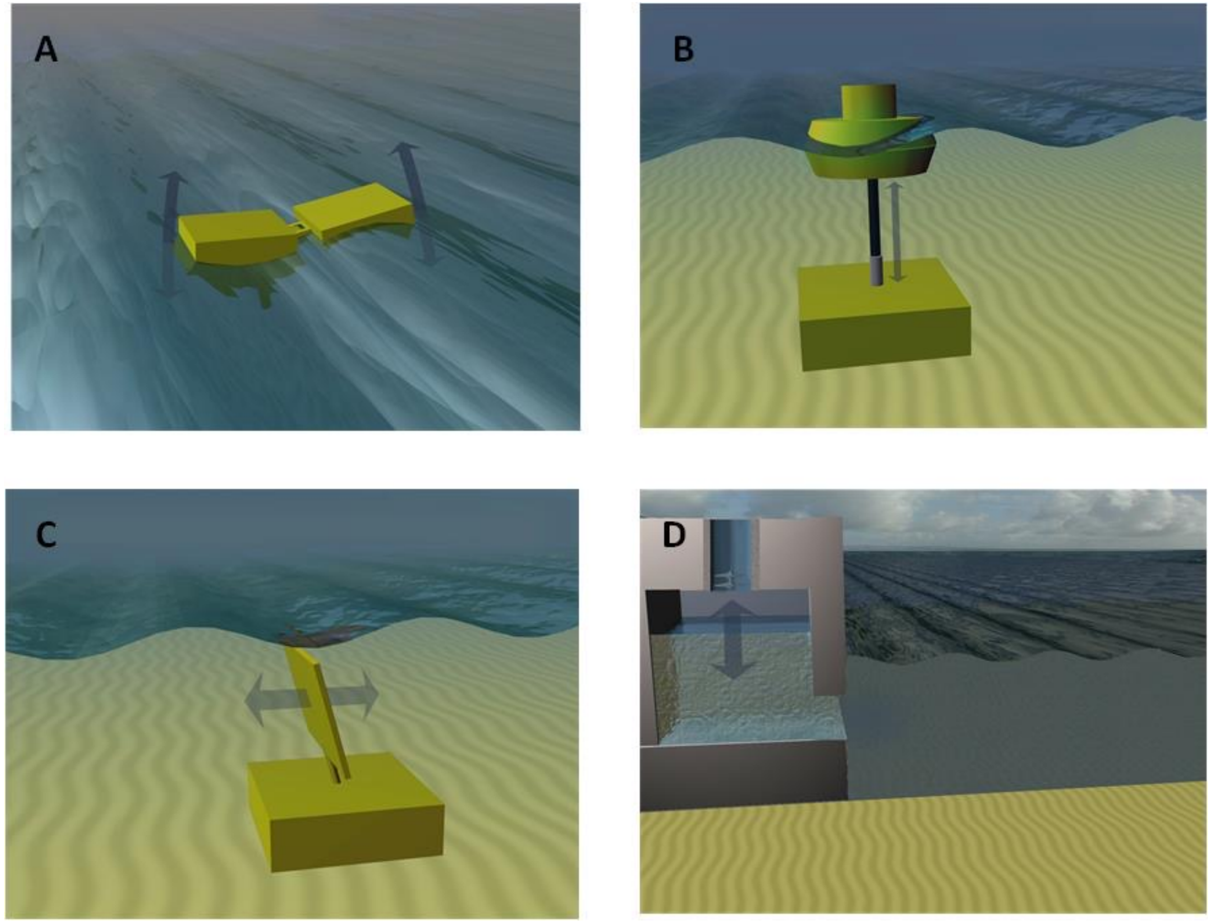


Figure 2-34: WEC devices: attenuator (A), point absorber (B), oscillating wave surge converter (C), oscillating water column (D).

Marine Energy

Wave Power

Wave Energy Converters

- An overtopping/terminator device (E) captures water from breaking waves to fill a reservoir to a level higher than the surrounding. A low-head turbine captures the potential energy to generate power.

- A submerged pressure differential device (F) is attached to the seabed. Operates due to pressure differential created by wave motion above. The difference in pressure is used to produce flow to drive a turbine and electrical generator.

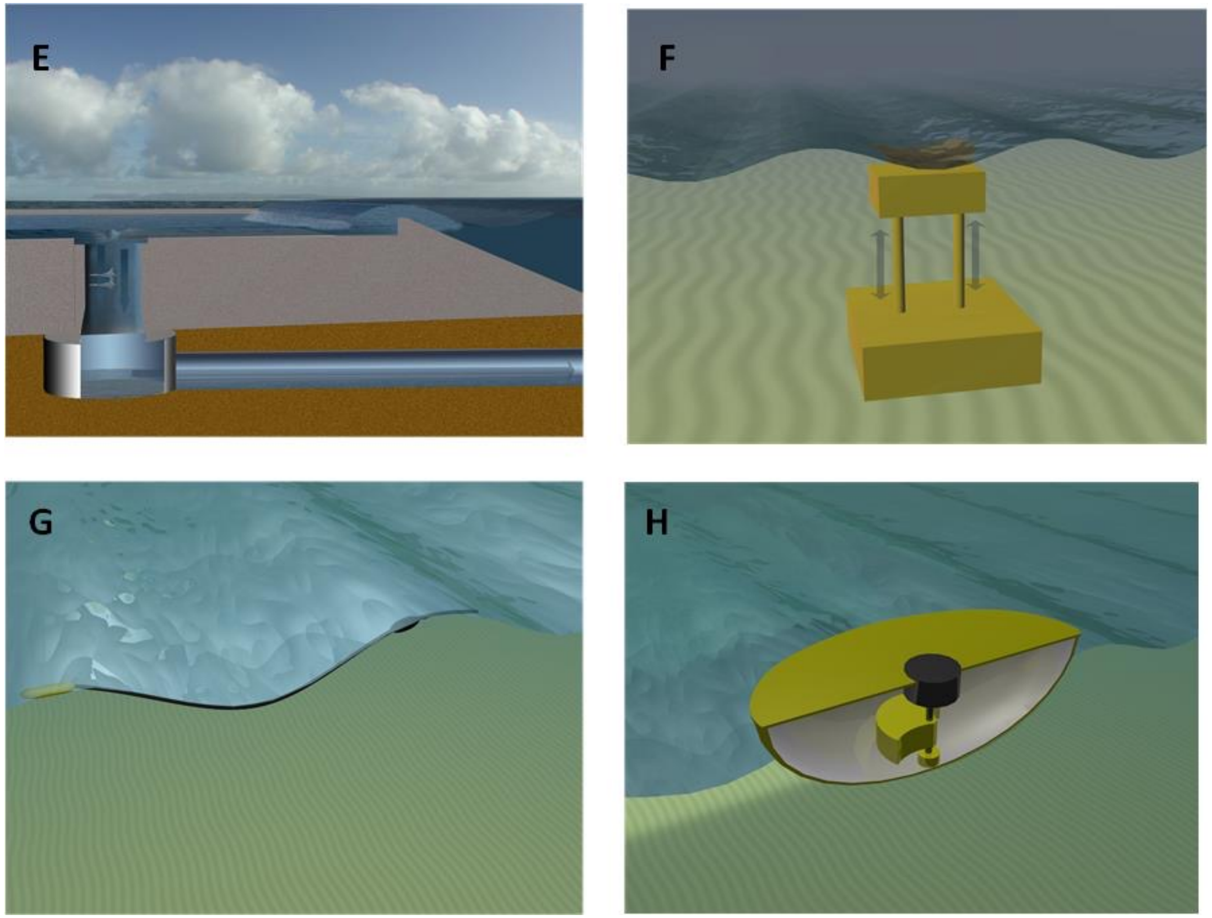


Figure 2-35: WEC devices: overtopping/terminator device (E), submerged pressure differential (F), bulge wave (G), rotating mass (H).

Marine Energy

Wave Power

- A bulge wave device (G) is a water filled rubber tube, moored to the seabed with one end facing incoming waves. As wave passes, pressure variations are created along the tube length, a bulge is created. Bulge grows as it travels through the tube and gathered energy drives a low-head turbine.
- In a rotating mass device (H), there are two forms of rotation, used to capture wave energy, heaving and swaying. There is either an eccentric weight driven by the motion or a gyroscope that causes precession. Movement is attached to a generator inside the device.

Wave Energy Converters

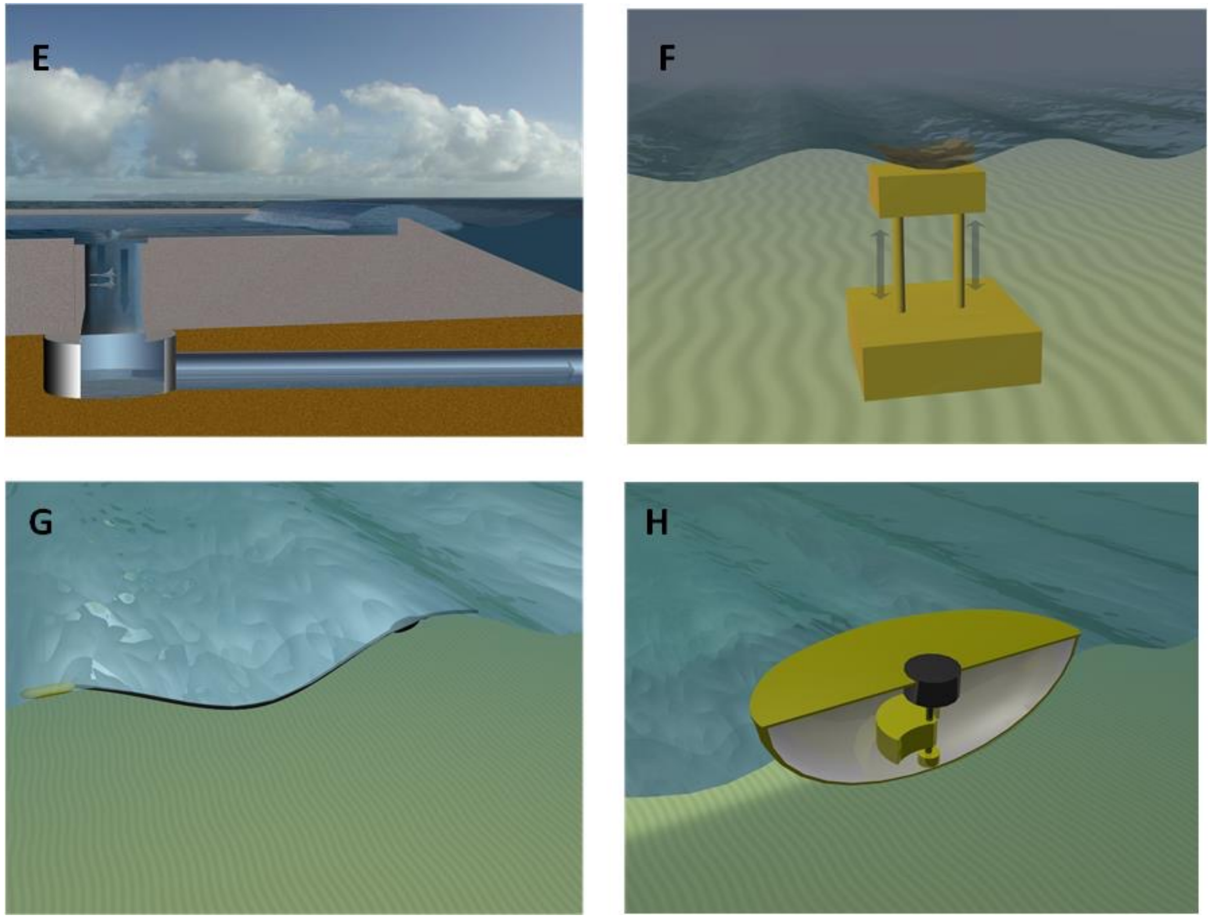


Figure 2-35: WEC devices: overtopping/terminator device (E), submerged pressure differential (F), bulge wave (G), rotating mass (H).

Marine Energy

Wave Power

Wave Energy Converters

- Most typical for shoreline applications are the oscillating water column devices
- For near-shore, common are the oscillating wave surge converters and the attenuator
- For offshore energy extraction, point absorber and terminator are most promising

Figure 2-36: The Pelamis Wave Energy Converter.

Marine Energy

Wave Power

Wave Energy Converters

- WEC devices raise environmental concerns
- High risk of fish and sea mammals hit by turbine blades or affected by presence of these structures in their habitant
- Underwater noise and electromagnetic fields due to operation of WECs
- Many WECs operating together form a wave farm
- Wave farm achieves larger production, hydrodynamical and electrical interaction between WECs
- Wave farms have operated in the UK and Portugal, but shut down
- Studies and tests for future commercial operation

Marine Energy

Tidal Power

- Tidal power is the capture of energy from tides
- Tides are the rise and fall of sea levels due to combined gravitational forces from the Moon, the Sun and Earth’s rotation
- Tides are predictable, large potential for energy production
- Not widely used due to high installation cost and limited eligible sites
- Rance and Sihwa Lake tidal power stations (240MW, 254MW) main contributors to global marine energy production

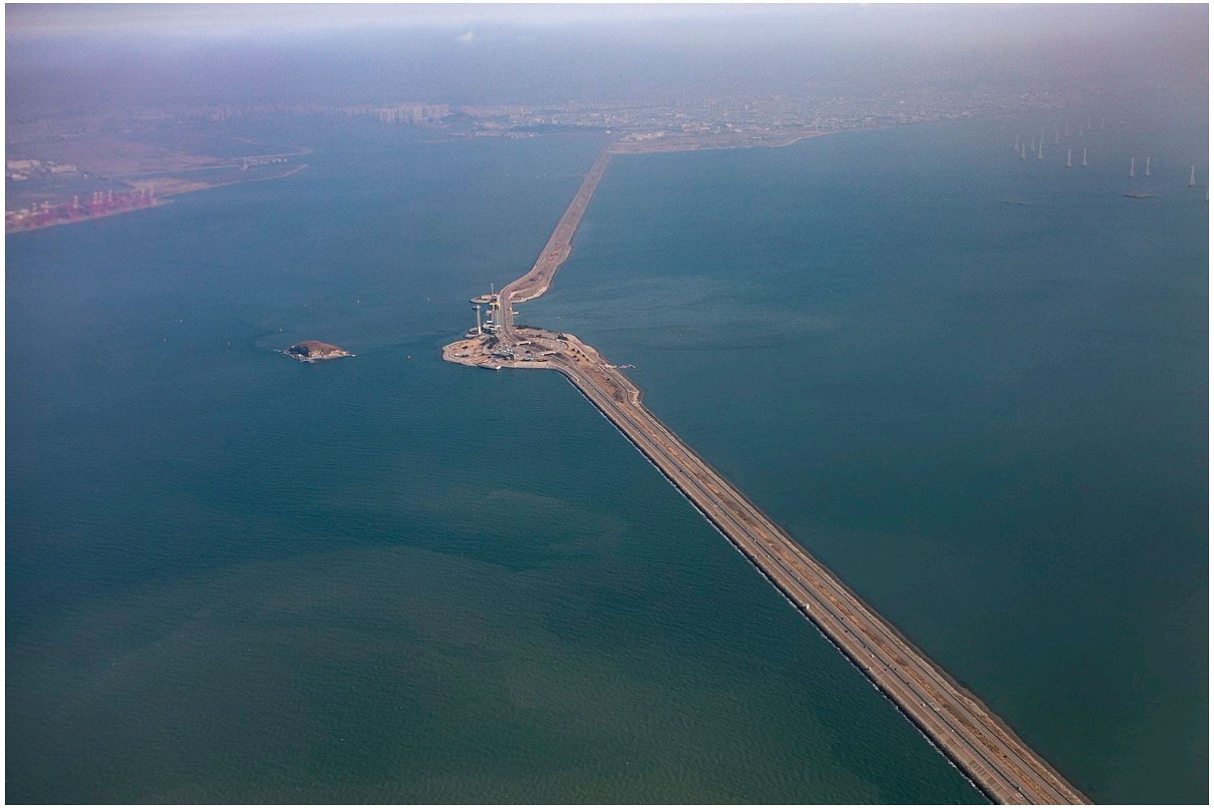


Figure 2-37: The Sihwa Lake Tidal Power Station in South Korea.

Marine Energy

Tidal Power

- Due to tidal forces on the ocean surface, a bulge in the water level is created, increasing the sea level temporarily
- Bulge moves towards the shoreline due to Earth’s rotation and a tide is created
- A tidal generator converts tidal flow energy to electricity
- The greater the tidal variation and tidal current velocities, the greater the energy production

Figure 2-38: The Rance Tidal Power Station in France.

Marine Energy

Tidal Power

- Three main methods for tidal power production:
  - *Tidal stream generator*
  - *Tidal barrage*
  - *Tidal lagoon*

Marine Energy

Tidal Power

- A tidal stream generator has the concept of a wind turbine
- Uses moving water kinetic energy to drive a turbine, which can be horizontal, vertical, open or ducted
- Due to higher density of seawater compared to air, slower water currents and smaller turbines can be used to exploit tidal energy, compared to wind energy

Tidal stream generator

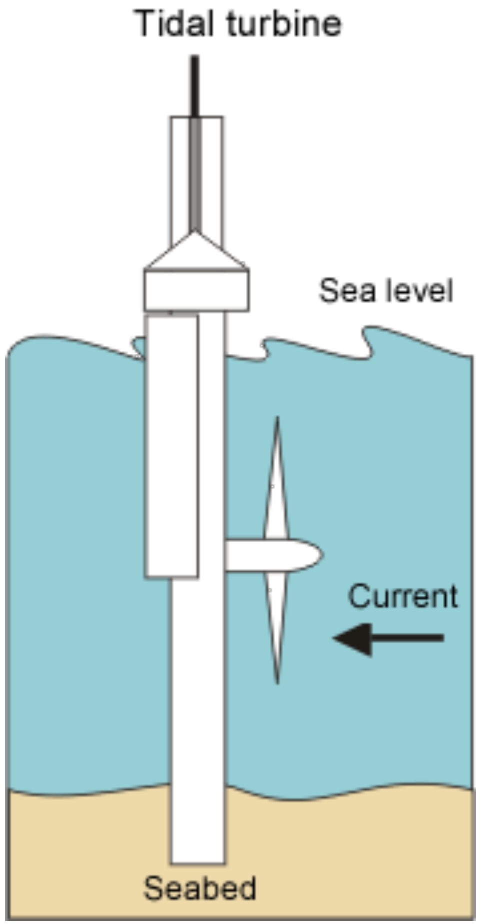


Figure 2-39: A tidal stream generator.

Marine Energy

Tidal stream generator

Tidal Power

- Tidal stream generators include:

  Axial turbines with blades facing flow direction,

  crossflow turbines with spinning blades perpendicular to flow direction,

  reciprocating devices with hydrofoil instead of spinning blades, pushed back and forth transverse to flow direction,

  venturi effect devices which have turbines inside a cylindrical duct to create second water flow.

Marine Energy

Tidal Power

- A tidal barrage system uses potential energy due to height difference between high and low tides, for energy production
- Used dams and sluice gates to capture potential energy and store it
- Dam is constructed across the entrance of a tidal inlet or basin, with bottom on the seabed
- Allows water to flow in during high tide and releases it during low tide, by controlling the sluice gates

Tidal barrage

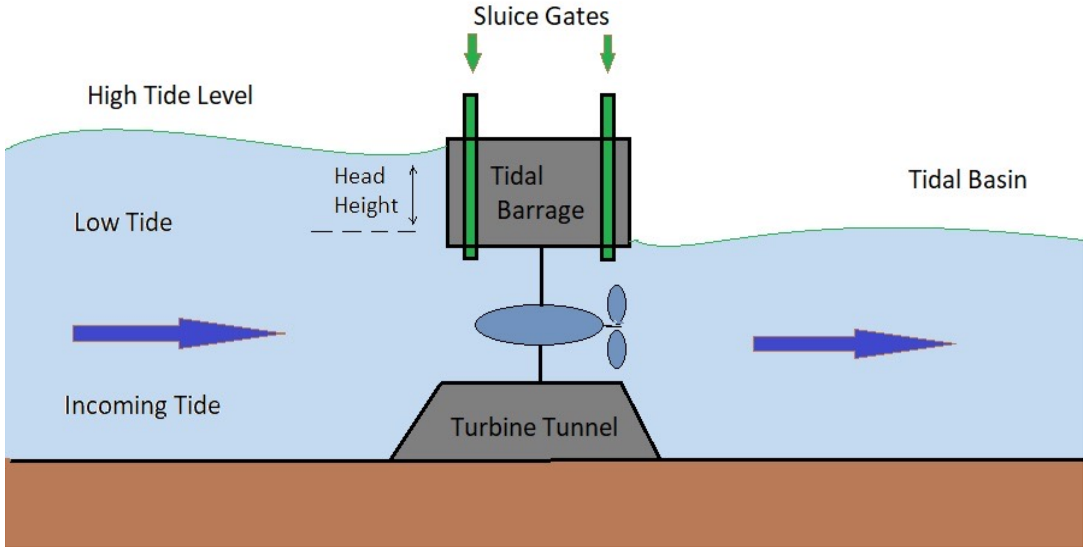


Figure 2-40: A tidal barrage flood generation system.

Marine Energy

Tidal Power

Tidal barrage

- Turbines, placed in the barrage wall, generate power as water flows in and out of the basin
- Rance and Sihwa Lake stations both tidal barrage systems
- Energy can be generated as water enters the reservoir on the incoming flood tide (tidal barrage flood generation system) or as water leaves the reservoir on the ebb flow tide (tidal barrage ebb generation system)
- In a two-way generation system, power is generated as water flows in both directions

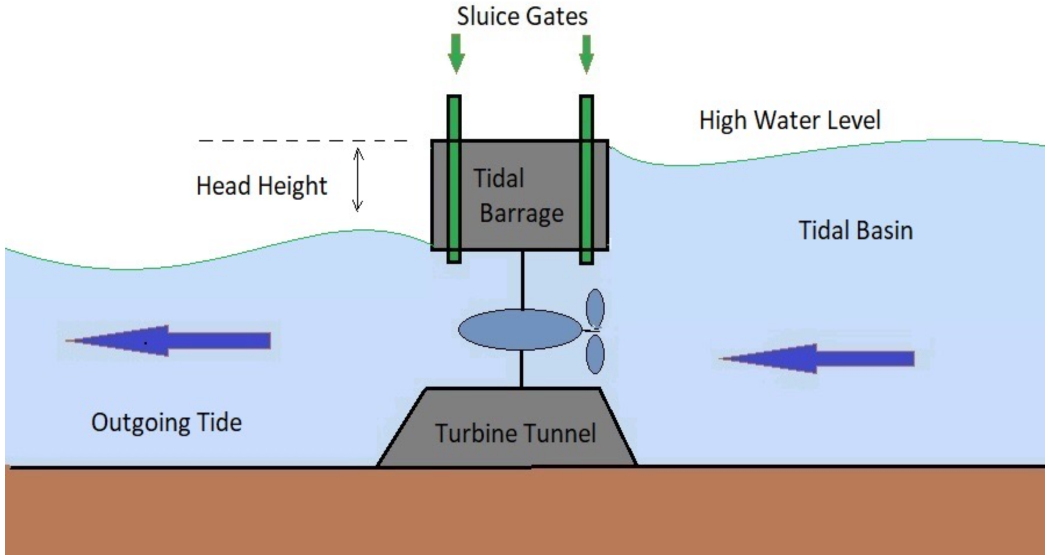


Figure 2-41: A tidal barrage ebb generation system.

Marine Energy

Tidal Power

Tidal lagoon

- Tidal lagoon is a modern design, consisting of circular retaining walls, embedded with turbines to capture tidal potential energy
- Reservoirs similar to those in tidal barrage systems
- No operational projects yet
- Tidal Lagoon Swansea Bay project in the UK was designed for operation but was cancelled

Marine Energy

Ocean Thermal Energy Conversion

- Ocean Thermal Energy Conversion (OTEC) generates electricity by using the ocean thermal difference between warm surface and cooler deep water to drive a Rankin cycle
- Temperature difference between surface ocean water and water at 1000m depth at least 20°C for OTEC to operate
- Temperature differences higher in the tropics
- OTEC could provide tens of times the energy from other ocean energy systems

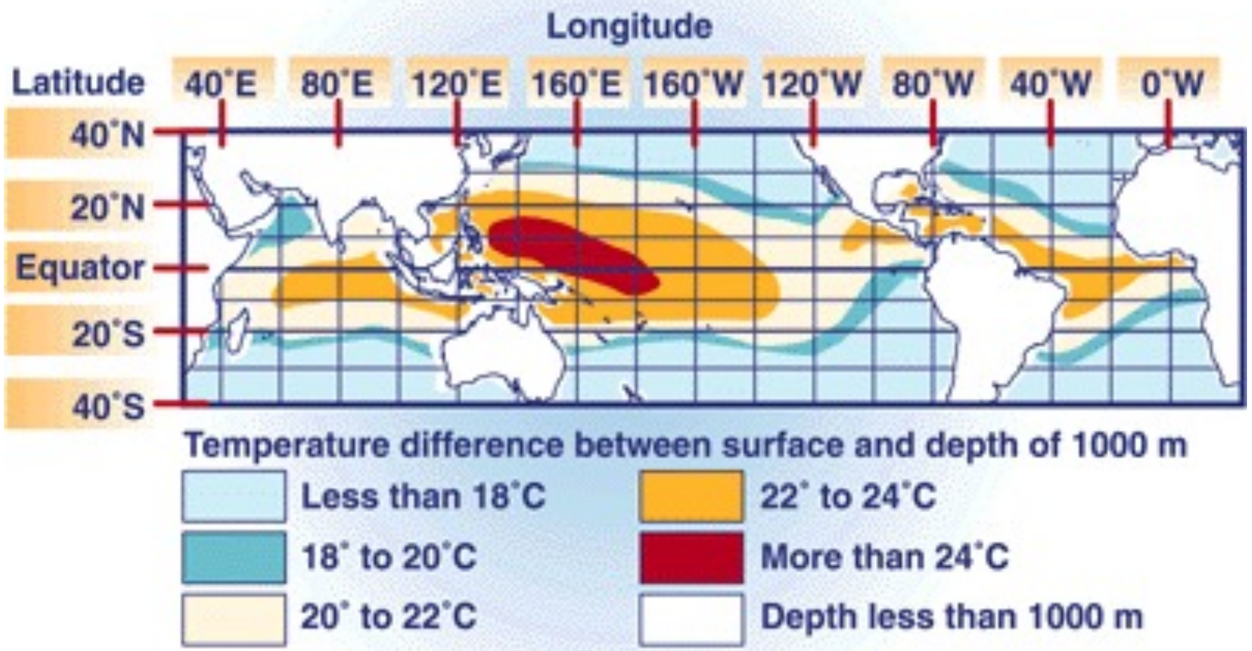


Figure 2-42: World map with the temperature difference between ocean surface water and depth of 1000m.

Marine Energy

Ocean Thermal Energy Conversion

- OTEC systems can be closed-cycle, open-cycle or hybrid
- In closed-cycle, a working fluid is turned to vapour due to heat transferred from warm surface seawater
- Vapour expands and drives a turbine/generator
- Vapour is lead to a condenser, turns to liquid as cold seawater passes through the condenser and is recycled through the system
- Low boiling point working fluid, e.g. ammonia

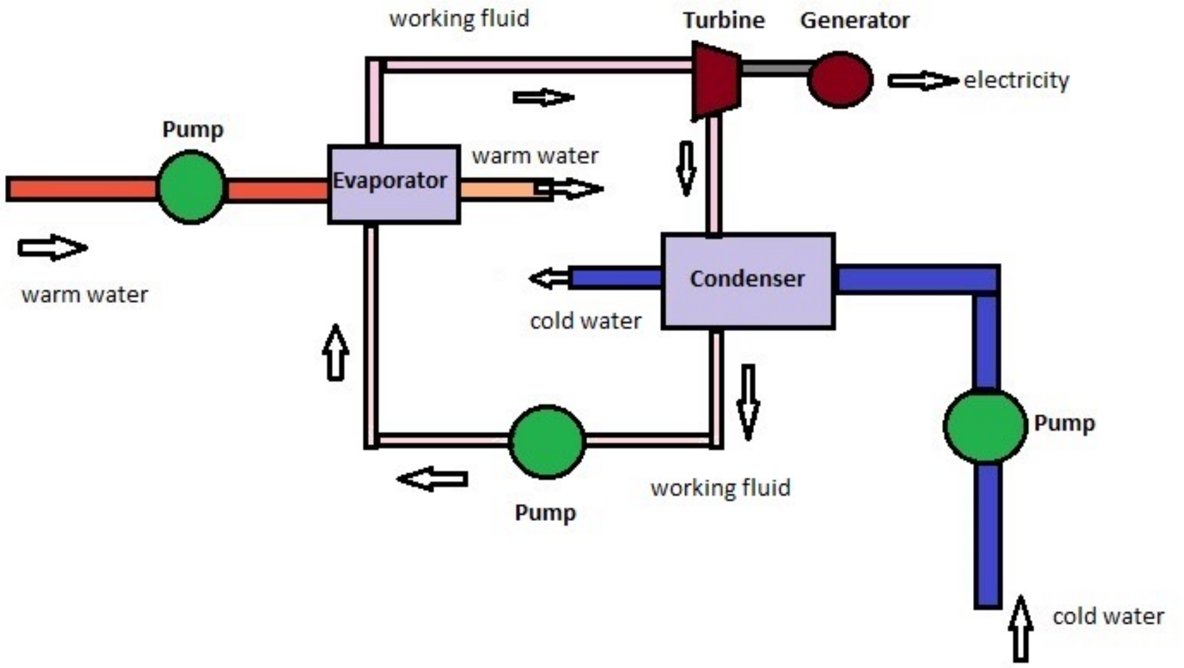


Figure 2-43: OTEC closed-cycle system.

Marine Energy

Ocean Thermal Energy Conversion

- In open-cycle, working fluid is the warm surface water, which vaporizes at surface water temperatures in a near vacuum
- Vapour (pure freshwater) expands and drives a low-pressure turbine attached to a generator
- It is then condensed due to cooler deep ocean temperatures
- Water can be used for drinking/irrigation if there's no direct contact of condenser and cool seawater
- If there's contact of condenser and cool seawater, more electricity is produced, water released into the ocean

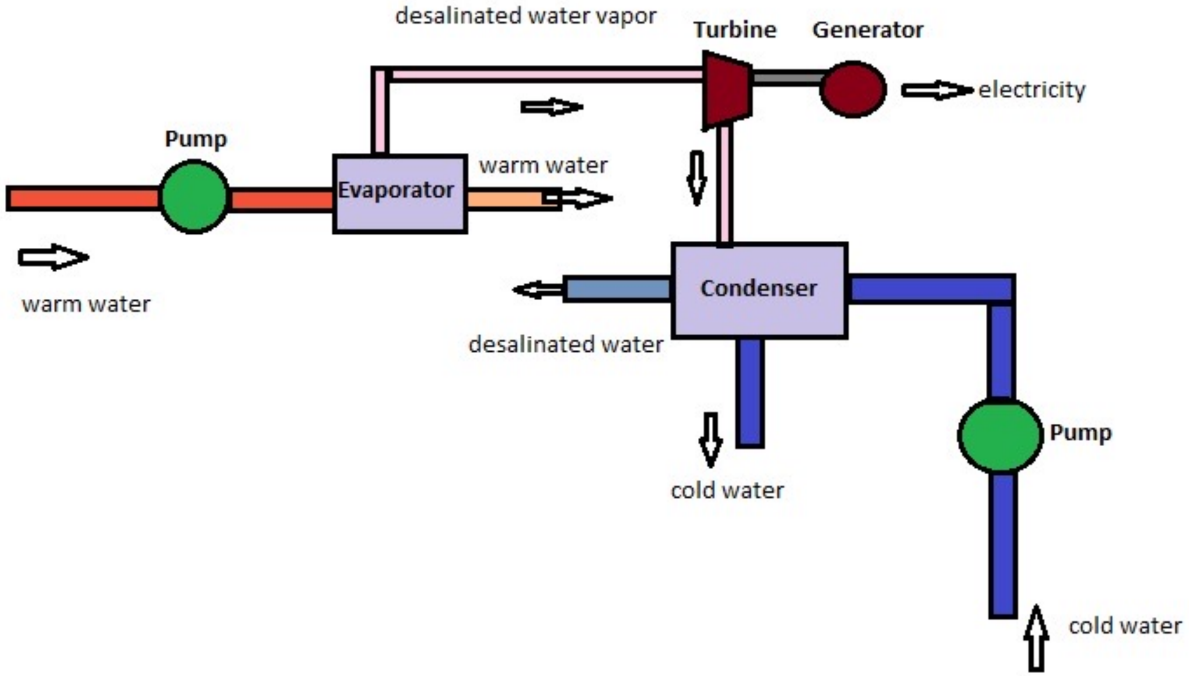


Figure 2-44: OTEC open-cycle system.

Marine Energy

Ocean Thermal Energy Conversion

- Open-cycle OTEC plant operated experimentally in 1993 at Keyhole Point, Hawaii, produced 80 kW of electricity
- A system tested in Japan in 1982 produced 40 kW of electricity
- Hybrid OTEC systems use parts of both closed and open-cycle systems to increase electricity production and produce freshwater. They have both ammonia and seawater as working fluids

Marine Energy

Salinity Gradient Power

- Salinity gradient power is the energy produced due to differences in salt concentration between saltwater (sea) and freshwater (river), as it happens at the mouth of rivers
- Two main methods for salinity gradient power production: reverse electrodialysis and pressure retarded osmosis
- Both methods rely on osmosis with membranes
- These systems are currently being tested and developed for commercial use in Norway and the Netherlands

Storage

- Energy storage systems transform energy into a form that can be stored and converted to electricity when needed
- Energy storage systems can be
  mechanical (pumped storage hydroelectricity, compressed air energy storage, flywheels),
  electrochemical (batteries),
  electromagnetic (capacitors, magnetic systems),
  thermal (phase change materials),
  chemical (biofuels, hydrogen storage)

Storage

- Important factors are energy density, efficiency, lifetime
- Efficiencies range between 50% and 80%
- Lifetimes range from minutes (e.g. non-rechargeable batteries) to a few years (e.g. lead acid batteries) or 100 years (dams)
- Another important factor is charging and discharging rate

Storage

Pumped storage hydroelectricity

- Pumped storage systems store energy in the form of potential energy of water, which is pumped from a low to a higher elevation reservoir
- Stored water is released through turbines to produce electricity
- Most cost-effective type
- Low energy density so large flow is required or large height difference
- High initial cost

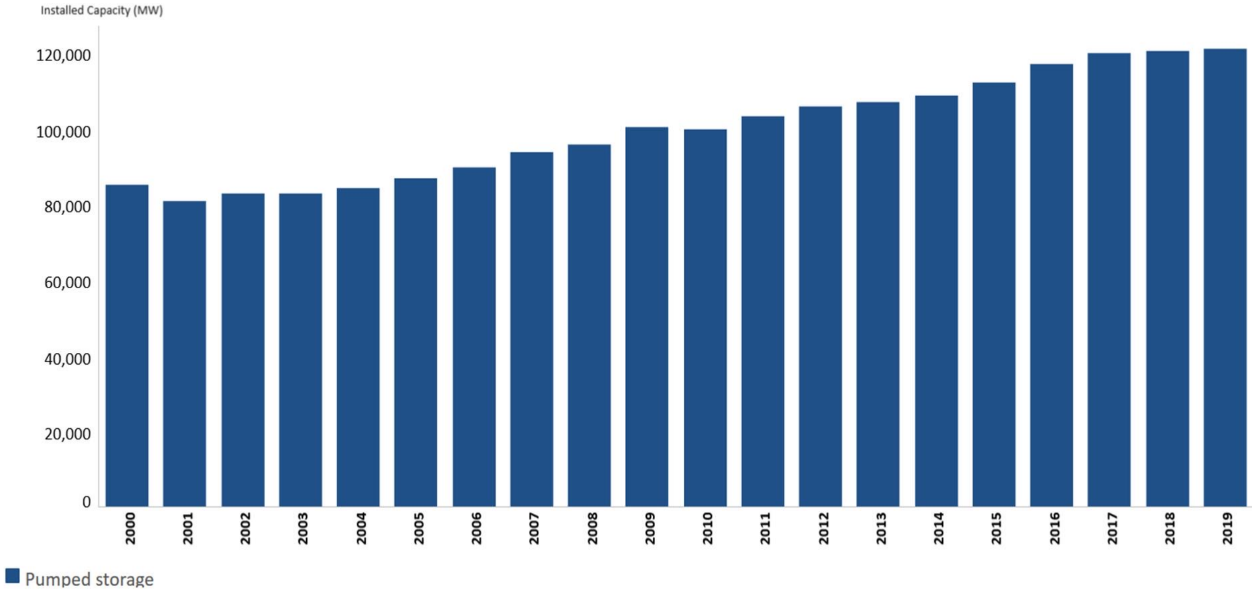


Figure 2-45: Pumped storage installed capacity (MW) from 2000 to 2019.

Storage

Pumped storage hydroelectricity

- Can respond to load changes within seconds
- Can provide peak-load power for fossil fuel and nuclear plants
- Usually 6 to 20 hours of hydraulic reservoir storage for operation
- China top country with over 30 GW installed capacity in 2019
- Largest pumped storage plants: Bath County in USA, Guangdong and Huizhou in China and Okutataragi in Japan

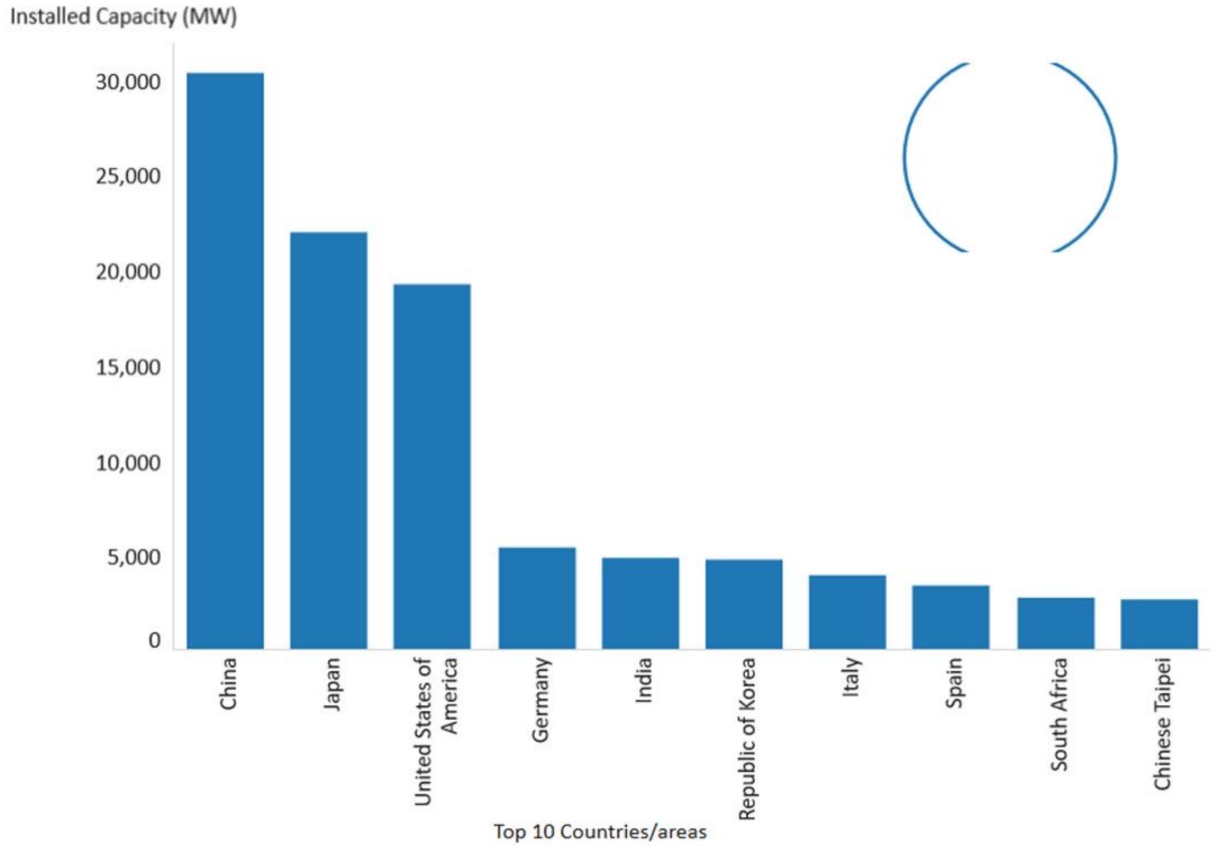


Figure 2-46: Pumped storage installed capacity (MW) for the top 10 countries for 2019.

Storage

Compressed air energy storage

- Compressed air energy storage (CAES) uses compressed air to store generated energy for later use
- Air is compressed and stored under pressure in an underground cavern or mine
- When needed, air is expanded to drive a turbine/generator
- Heat is generated during compression and is removed during expansion
- Depending on how the system handles heat during compression, process can be diabatic, adiabatic, isothermal or near-isothermal

Storage

Compressed air energy storage

- In diabatic processes, much of generated heat is dissipated in the atmosphere by using intercoolers. Decreased efficiency but only type to have been used commercially, e.g. CAES plant in McIntosh, Alabama and the plant in Huntorf, Germany
- In adiabatic processes, generated heat is kept in the system and returned to heat the air during expansion. Higher efficiencies, no commercial use
- An isothermal process tries to maintain operating temperature by constant exchanging heat with environment. In reality the process is never isothermal
- In near-isothermal, compression is done near a large thermal mass in which heat from compression is transferred

Storage

Flywheel energy storage

- Flywheel is a rotating mechanical device, connected to a motor-generator, may be enclosed in vacuum chamber
- Spins to high speed and rotational energy is generated, converted to electricity when needed. Recharged with the motor
- Energy stored is proportional to device's moment of inertia and square of its angular velocity
- Long lifetimes, doesn't require a lot of maintenance, fast reaction times, efficiency up to 90%
- Have been used in transportation, buses, train, cars, experimentally

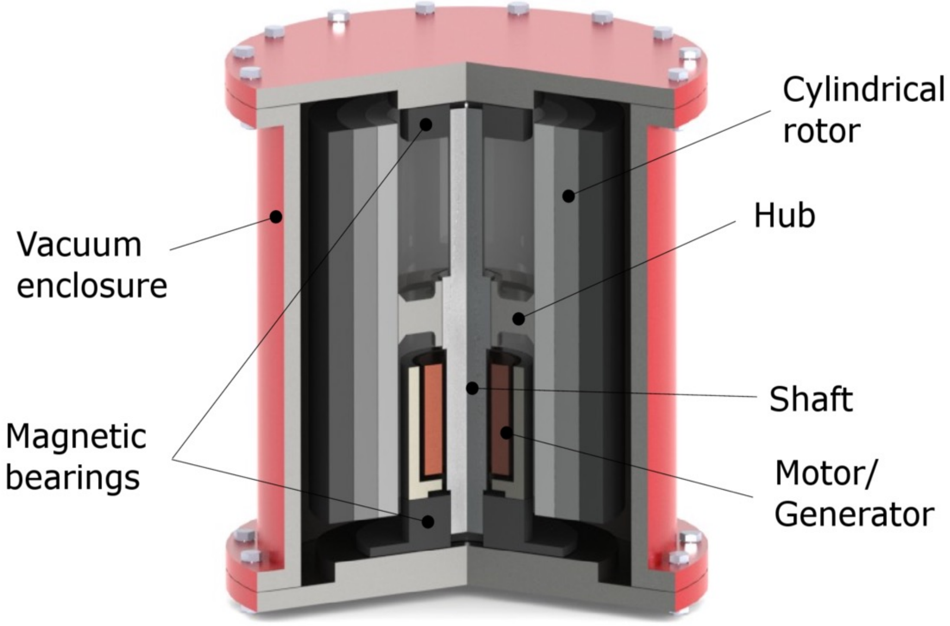
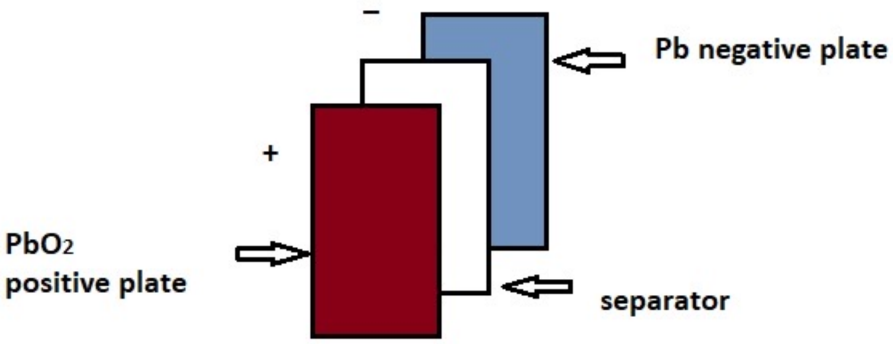


Figure 2-47: Diagram of a flywheel device.

Storage

Batteries

- Batteries convert stored chemical energy into electrical and opposite in charge cycle
- Consists of one or more electrochemical cells, each with two electrodes immersed in an electrolyte, which allows transport of ions
- Storage capacity depends on battery age, temperature, rate of discharge
- Lead-acid stores chemical energy in the potential difference of the negative lead side and positive PbO2 side, plus the aqueous sulfuric acid
- Lead-acid batteries have low energy-to-weight and energy-to-volume ratios but high power-to-weight ratio, low cost, used for remote village power and stand-alone systems



$$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

Figure 2-48: Lead-acid battery chemistry.

- E.g. 10MW, 4-h system in Chino, California and 20MW, 40-min system in San Juan, Puerto Rico

Storage

Batteries

- Lithium-ion batteries have high energy density, efficiency~100%, long cycle life, higher cost.
- Anode is carbon graphite and cathode consists of lithiated metallic oxide, while storage medium contains mix of lithium salts and organic carbonates.
- Sodium-sulfur batteries are constructed from liquid sodium and sulfur. High energy density and efficiency, long cycle life, inexpensive.
- Operate at temperatures 300-350°C, suitable for stationary applications.
- Support stand-alone systems or electric grid. Good option for wind farms, solar power stations.
- E.g. 34 MW, 245 MWh unit in a wind farm in northern Japan

Storage

Batteries

- In a flow battery, there are two chemical components dissolved in liquids, pumped through the system on separate sides of a membrane
- The two external electrolyte reservoirs are separated from the electricity converter unit
- Three types: vanadium redox, polysulfide bromide, zinc bromide battery
- Can support off-grid village power, large power applications, release energy for extended period
- High operating, maintenance costs
- E.g. 1.5 MW system in a semiconductor fabrication plant in Japan

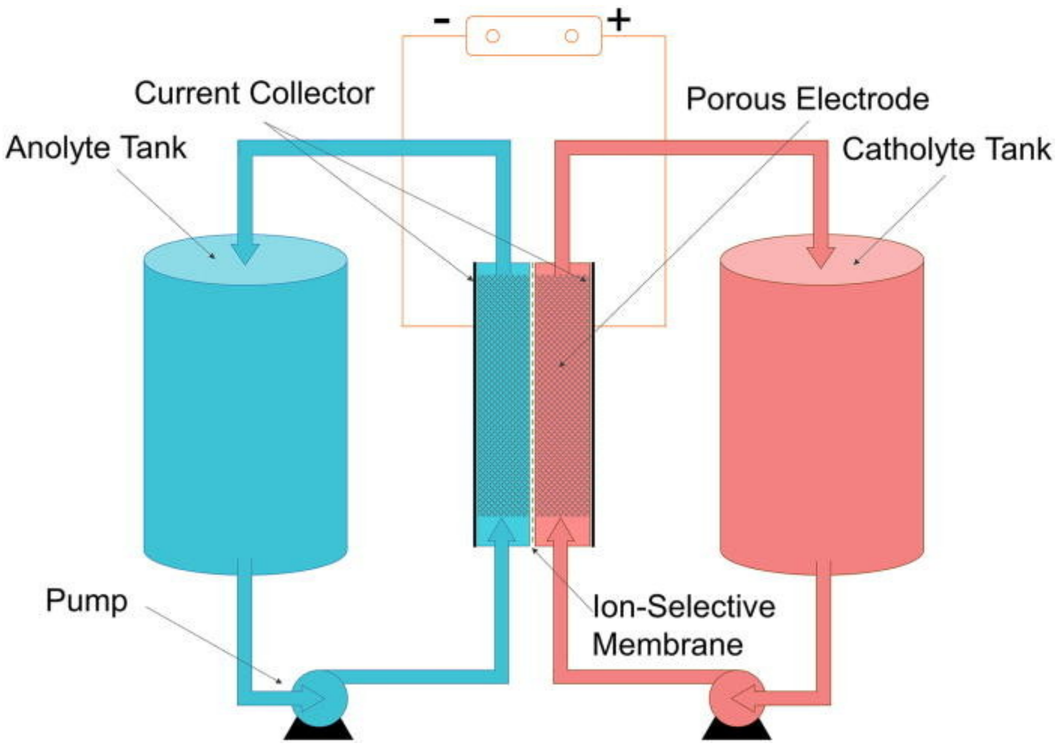


Figure 2-49: Diagram of a flow battery.

Storage

Superconducting magnetic energy storage

- Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field, created by the direct current flow in a superconducting coil
- Coil must have been cryogenically cooled to temperatures lower than its superconducting critical temperature
- SMES systems have long lifetimes, very good response and efficiencies up to 95%
- No energy loss over time
- Considerable cost for refrigeration and superconductive coil
- Several 1MWh operating worldwide for clean power quality at manufacturing plants
- Can provide grid stability or used in utility applications
- SMES systems in Wisconsin, USA used to enhance stability on a transmission loop

Storage

Capacitors

- Capacitors store energy on two conductors, separated by a non-conductive region, which can be a vacuum or a dielectric
- Conductors hold equal opposite charges and dielectric creates electric field
- Supercapacitors store electrical charge in an electric double layer, formed between each of the electrodes and the electrolyte ions
- Supercapacitor has long life, fast response, can be used for micro grid energy storage, used in conjuction with chemical batteries

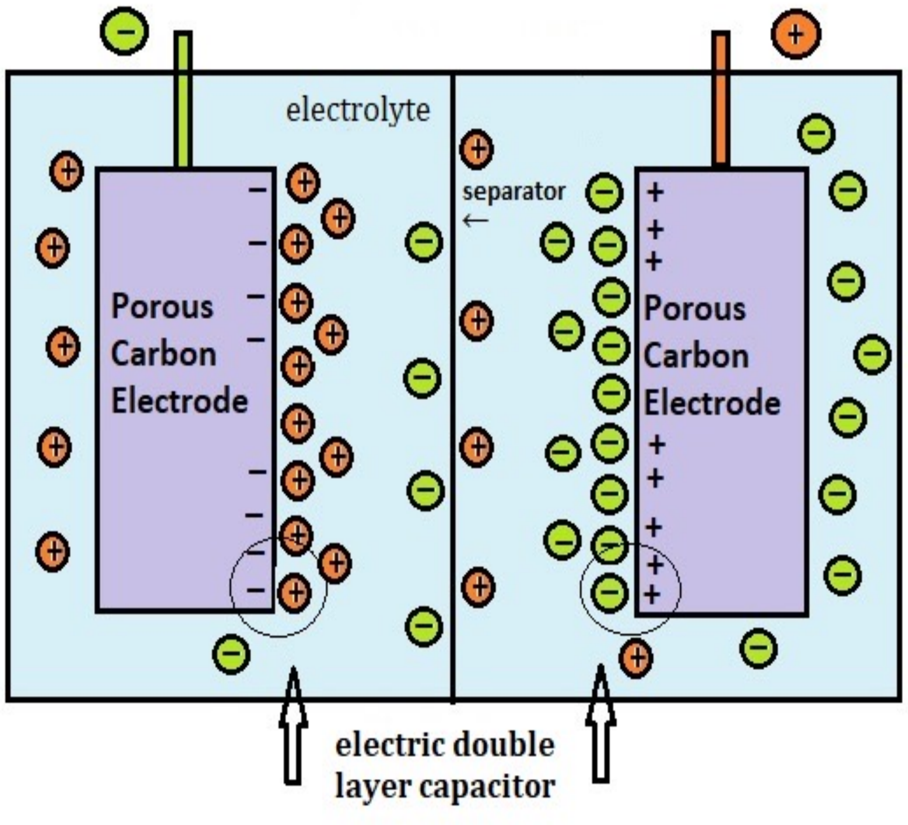


Figure 2-50: Illustration of a supercapacitor.

Storage

Phase change materials

- A phase change material releases/absorbs energy, at almost constant temperature, as it changes phases to provide heating/cooling
- Liquid-solid phase change is used
- Substance should have large latent heat and high thermal conductivity
- Two main types are organic materials, derived from petroleum, plants, animals and salt hydrates, which use salts from the sea, mineral deposits or by-products
- Used for commercial applications, e.g. heating pads
- Biggest potential is for building heating and cooling

Storage

Hydrogen storage

- In hydrogen storage, hydrogen is produced by electrolysis, either by alkaline electrolysis or Proton Exchange Membrane (PEM) electrolyzers
- Can be stored in pressurized vessels or in underground salt caverns
- Can be re-electrified in fuel cells or burned in gas power plants with efficiencies up to 60%
- Can be used as fuel for fuel cell cars or injected into natural gas pipelines
- Efficiency of electrolysis to fuel cell to electricity is around 50%
- E.g. 6MW hydrogen storage plant using PEM technology in Germany to convert excess wind power to hydrogen to use in fuel cells or natural gas supply.
  2MW PEM facility in Ontario to produce hydrogen from water through electrolysis

Issues and Aspects

Environmental concerns

- Solar and concentrated solar power applications need large land areas
- Wind power applications create noise and visual concerns, effects on wildlife, birds, bats
- Biomass production needs large land areas, greenhouse gases emissions
- Geothermal production can cause land subsidence, seismic activity, risk of depletion
- Hydropower applications have visual impact, impact on fish, displacement of population, risk of dam collapse
- Marine power applications affect sea life and raise concerns for ships

Issues and Aspects

Politics and Regulations

- Approval and permits from agencies and governmental departments
- Environmental impact analysis
- Permits for construction, safety regulations
- Eligibility of land, national parks, wild life protected areas, historical areas
- Need for incentives, like tax reductions, subsidies, regulations in favor of renewable energy advancement
- Policies for integration of renewable energy to the power grid, portfolio standards
- Tax incentives, investment and production tax deduction, property tax reduction, tax credits for research development of equipment, taxes for use of conventional fuel

Issues and Aspects

Politics and Regulations

- Europe promoted wind energy with price support for kilowatt hour production and capacity based method
- 1990 law in Germany made utilities buy renewable energy from power producers at a minimum price, defined by government
- China implemented policies for wind farm installations, mandated the majority of wind turbine components be manufactured within the country
- Spain and Germany lead the way in 2009 in PV installed capacity due to feed-in tariff systems
- Incentives are the reason for increase in ethanol production

Issues and Aspects

Economics

- Factors to consider: installation cost, land cost, value of produced power, cost of energy from competitive sources
- Cost depending on size, type and manufacturing company
- Energy resource and its variations is an important factor
- Operation, maintenance, insurances, inflation, legal costs, incentives
- Land consideration, contract to sell generated electricity, access to transmission lines
- Levelized cost of energy (LCOE) is calculated by taking into account the sum of costs of the project over its lifetime divided by the sum of electricity produced over its lifetime

Issues and Aspects

Economics

- Solar power and wind power technologies show decrease in LCOE values. No fuel costs, no variations in operation, maintenance costs: LCOE proportional to capital costs
- Technologies with fuel costs have LCOE affected by capital costs and fuel costs
- Renewable energy becomes cheaper due to technological progress, increased competition and incentives
- Solar and wind power expected to produce 50% of world's energy by 2050
- Most economic option for new grid-connected capacity in sites with good resources

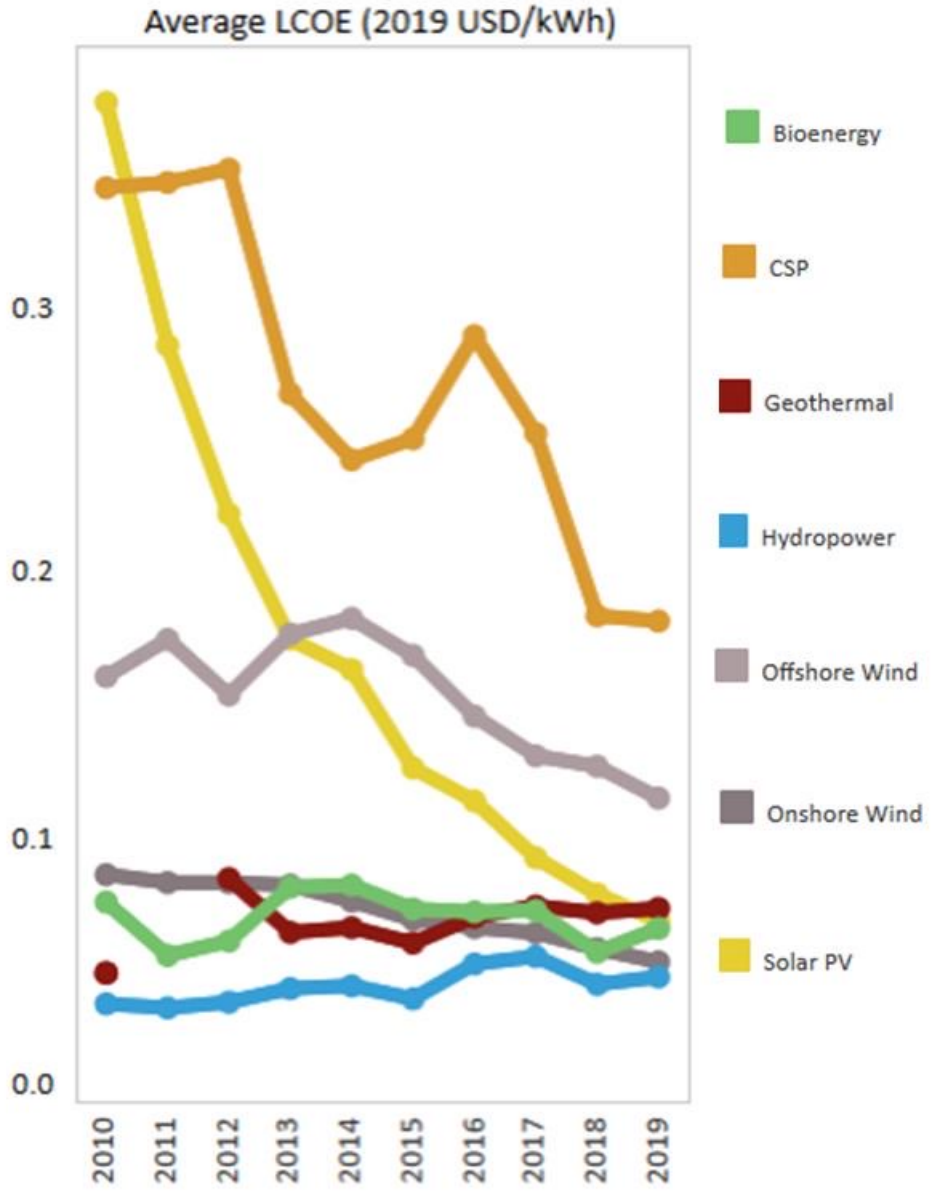


Figure 2-51: Average levelized cost of energy (LCOE) (2019 USD/kWh) trend for renewable technologies.

- In this chapter, geothermal energy, hydropower and marine energy were introduced, with their characteristics, operation and worldwide status. The basic storage devices were described and renewable energy aspects and issues were discussed.

Summary

Introduction and Overview of Renewable Energy Resources (RESs) (2/2)

Thank You

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REDER
Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

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Dr. Andreas Kazantzidis

Introduction to Renewable Energy

Lecture 3: Physics of sunlight and photovoltaics

Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

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Section Outline

In this section, solar radiation is presented with its spectrum and the geometry of the Sun-Earth system. The fundamentals of energy conversion in photovoltaic solar cells are described and the main types of photovoltaic technologies are given.

Section 1

Physics of sunlight and photovoltaics

This week's topics…

- Solar Radiation
- Energy Conversion in Solar Cells
- Photovoltaic Technologies
  - Crystalline silicon
  - Amorphous silicon
  - Cadmium-telluride cells
  - CIGS cells
  - Hybrid cells
  - Other cell technologies

Solar Radiation

- Sun data:
  - diameter: 1.39×10^9 m
  - mass: 1.989×10^{30} kg
  - distance from Earth: 1.496×10^8 km
  - composition: hydrogen (92%), helium (8%)
  - black body with effective temperature 5777 K
  - temperature at the centre: 15.7×10^6 K

- Energy generated through nuclear fusion
- Hydrogen is converted to helium

Solar Radiation

- Energy is transferred to the surface by radiative and conductive processes and radiated to space
- Photosphere is where most emitted radiation comes from, effective temperature of 5777 K
- Sun radiates power P=3.845x10^{26} W in all directions
- The solar constant is energy received on a unit area of surface perpendicular to radiation’s direction, per unit of time, outside the atmosphere

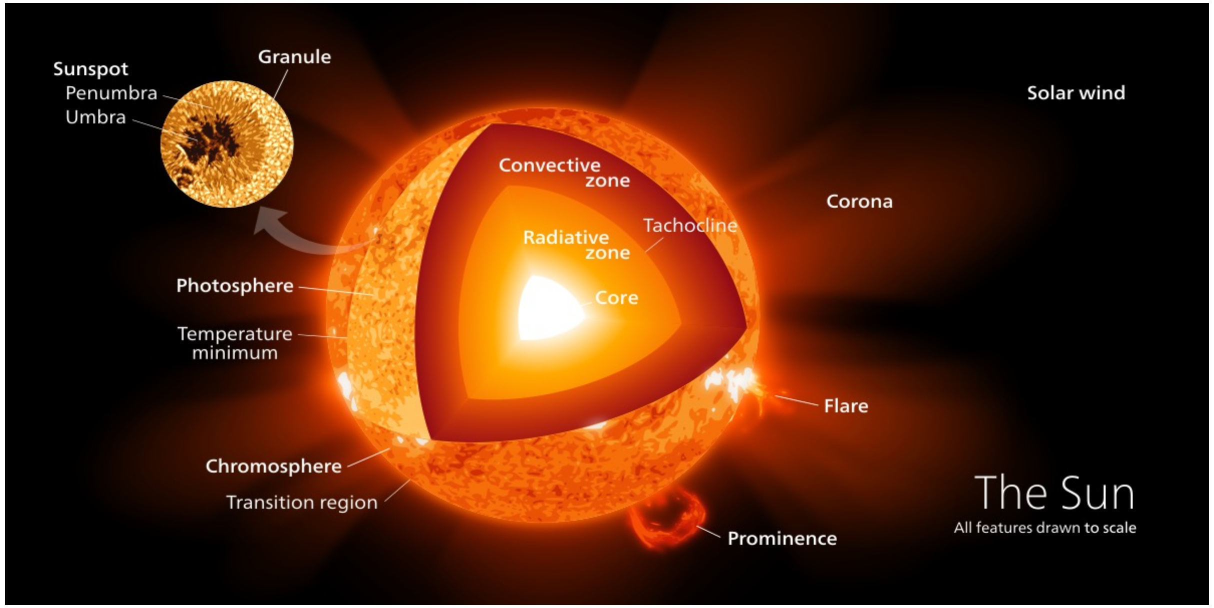


Figure 3-1: Structure and layers of the Sun.

$$G_{SC} = \frac{Psun}{4\pi r^2} = \frac{3.845 * 10^{26} W}{4\pi(1.496 * 10^{11} m)^2} = 1367\ W/m^2$$

Solar Radiation

- Spectral distribution of Sun’s radiation follows Planck’s law for a blackbody with effective temperature 5777 K
- Spectrum outside the atmosphere is for Air Mass (AM)=0
- Radiation at sea level, AM=1.5 average spectrum

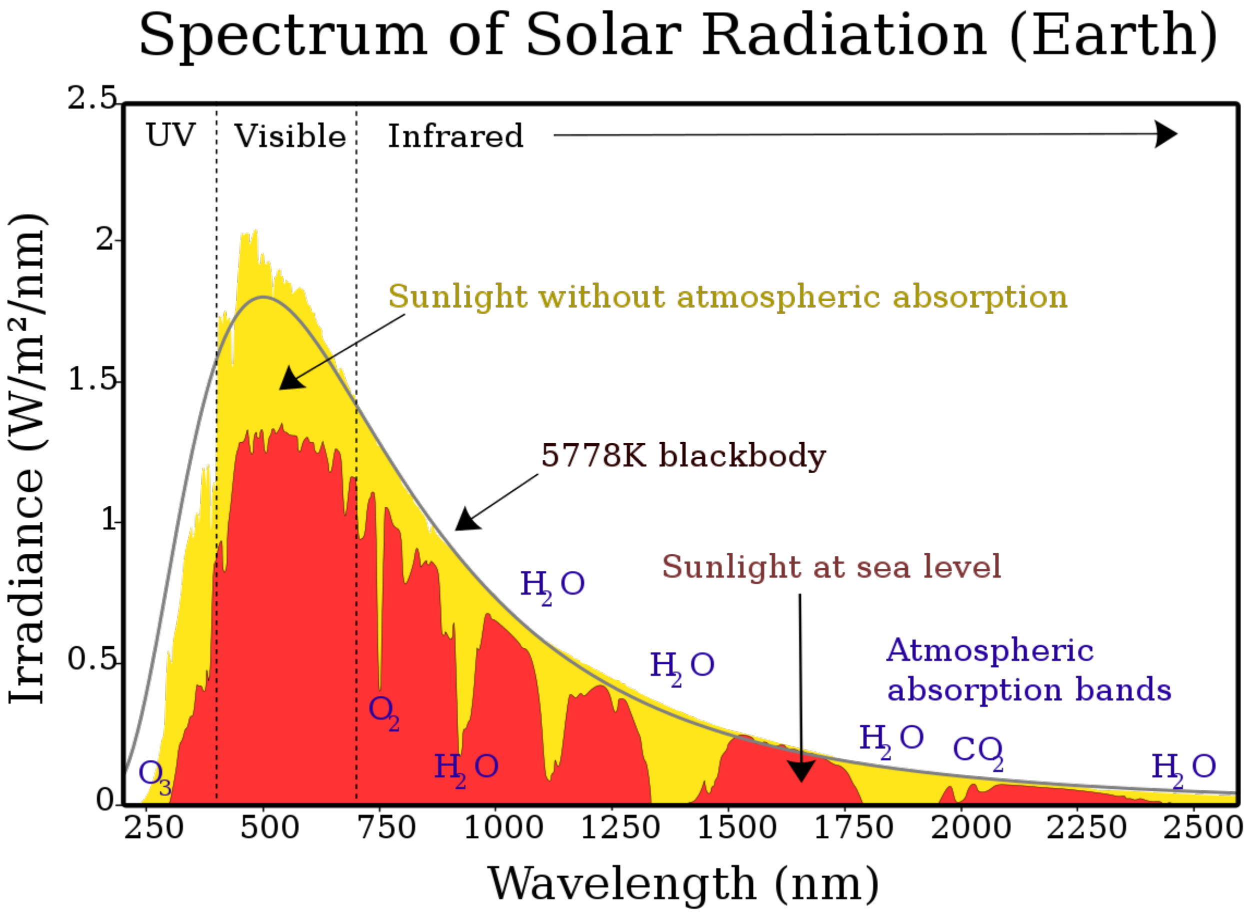


Figure 3-2: Solar spectrum outside the atmosphere and at sea level.

Solar Radiation

- As solar radiation travels through the atmosphere it is subject to:
  - Absorption from molecules (O2, O3, H2O, CO2..)
  - Reflection
  - Rayleigh scattering from particles smaller than incident wavelength
  - Mie scattering from particles larger than incident wavelength

Solar Radiation

Air Mass

- Air mass (AM) is described as the ratio of the mass of atmosphere direct radiation passes through to the mass it would pass if it travelled in a vertical direction

$$AM = \frac{1}{cos\theta_z}$$

θ_z is the zenith angle

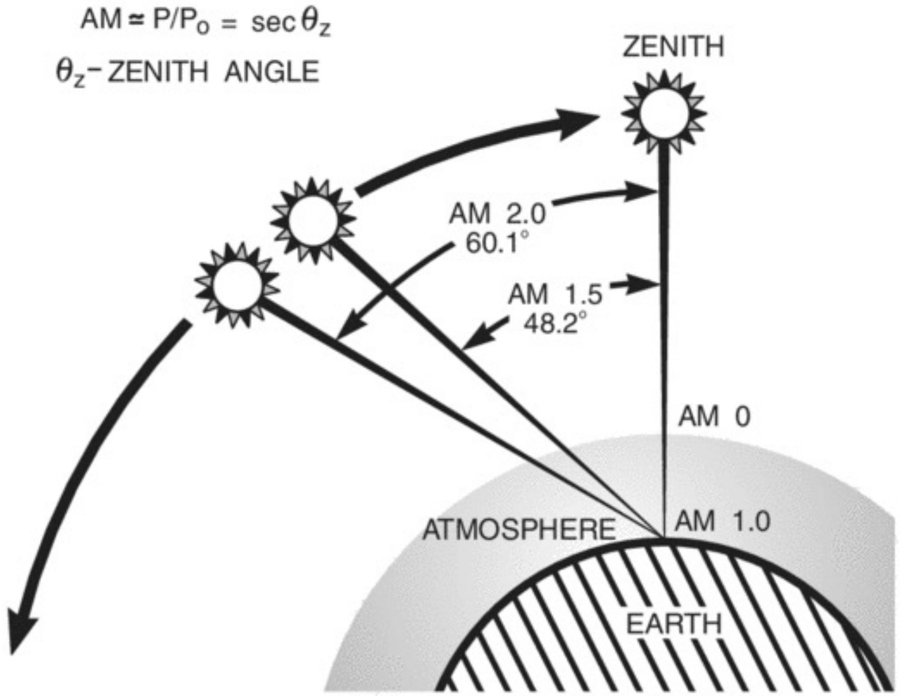


Figure 3-3: Illustration of Air Mass.

Solar Radiation

Direct and Diffuse Radiation

- Global radiation is the sum of direct and diffuse components

$$E_G = E_{Direct} + E_{Diffuse}$$

- Global radiation on a horizontal level

$$E_{GH} = E_{Direct} * cos\theta_Z + E_{Diffuse}$$

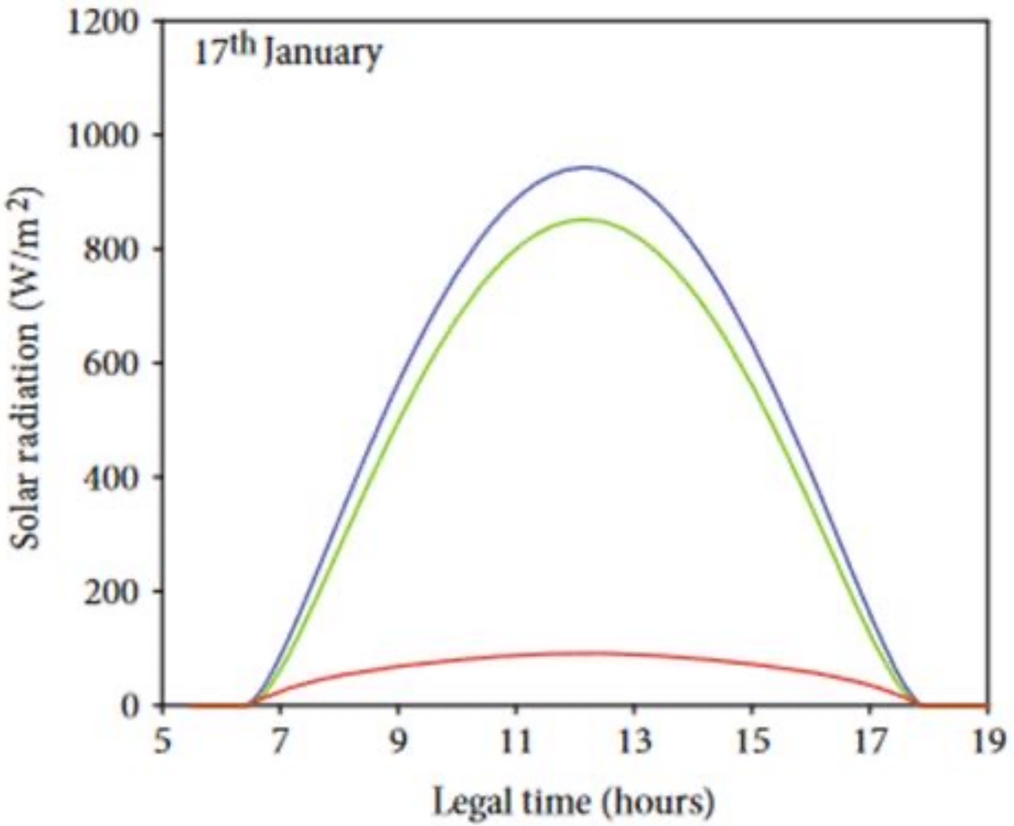


Figure 3-4: Example of modelled daily variations of direct (green), diffuse (red) and global (blue) radiation on a clear day.

Solar Radiation

Geometry of Sun-Earth System

- Earth’s rotational axis is tilted at 23.45°
- Declination angle, δ, ranges between - 23.45° and 23.45°
- Sun’s position is determined by θ_Z:zenith angle, α_S:solar altitude, γ_S:solar azimuth

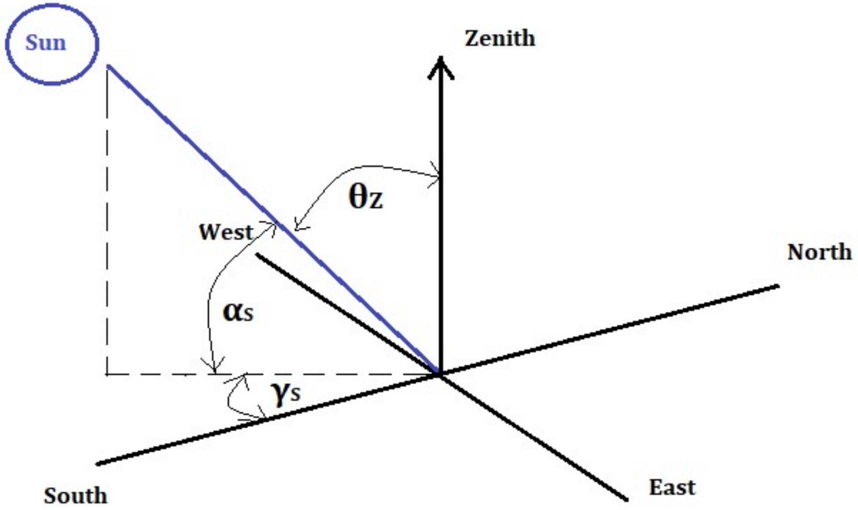


Figure 3-6: Solar angles on a horizontal plane.

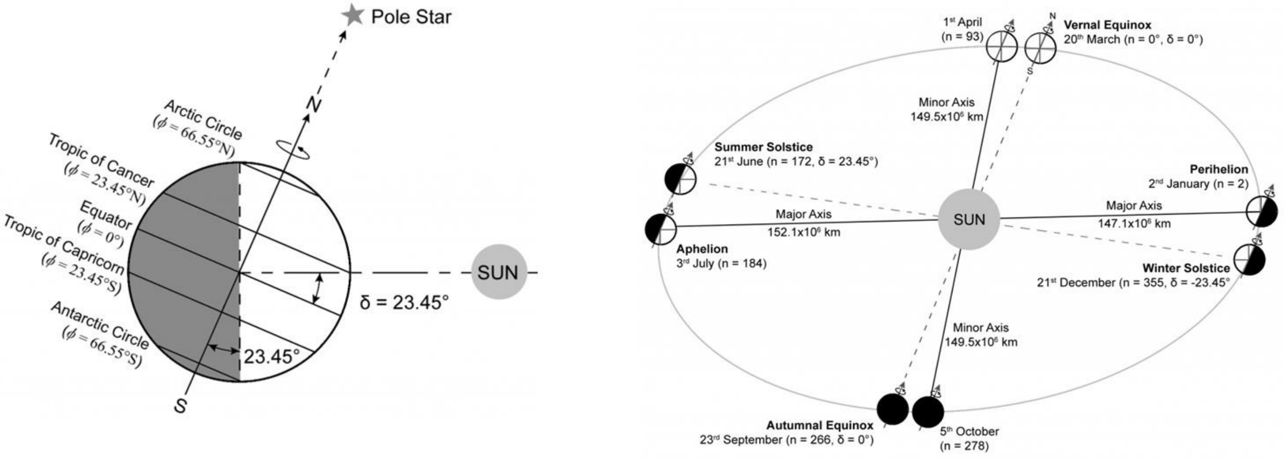


Figure 3-5: Declination angle and its variation during the year.

- β is the inclination angle of the panel surface with horizontal level

Solar Radiation

Sun Path

- Local Solar Time (LST): solar noon when Sun crosses meridian
- Local Standard Time differs due to time zone adjustments, daylight savings and Earth's orbit eccentricity

$$solar\ time - standard\ time = 4(L_{st} - L_{loc}) + E$$

- L_{st}: longitude of the standard meridian of the local time zone
- L_{loc}: longitude of the site
- E: equation of time

$$E = 229.2(0.000075 + 0.001868cosB - 0.032077sinB - 0.014615cos2B - 0.04089sinB)$$

$$B = (n-1)\frac{360}{365}$$

Solar Radiation

Sun Path

- Calculation of solar altitude and azimuth
- ω: hour angle
- φ: latitude

$$\omega = (LST - 12) * 15°$$

$$sin\alpha_S = sin\varphi * sin\delta + cos\varphi * cos\delta * cos\omega$$

$$sin\gamma_S = \frac{cos\delta * sin\omega}{cos\alpha_S}$$

Solar Radiation

Radiation on Tilted Surfaces

- ○ Photovoltaics are placed in tilted position
- ○ They form an inclination angle with the horizontal plane
- ○ Total radiation incident on a tilted surface

$$E_{tilt} = E_{Dir,tilt} + E_{Dif,tilt} + E_{Ref,tilt}$$

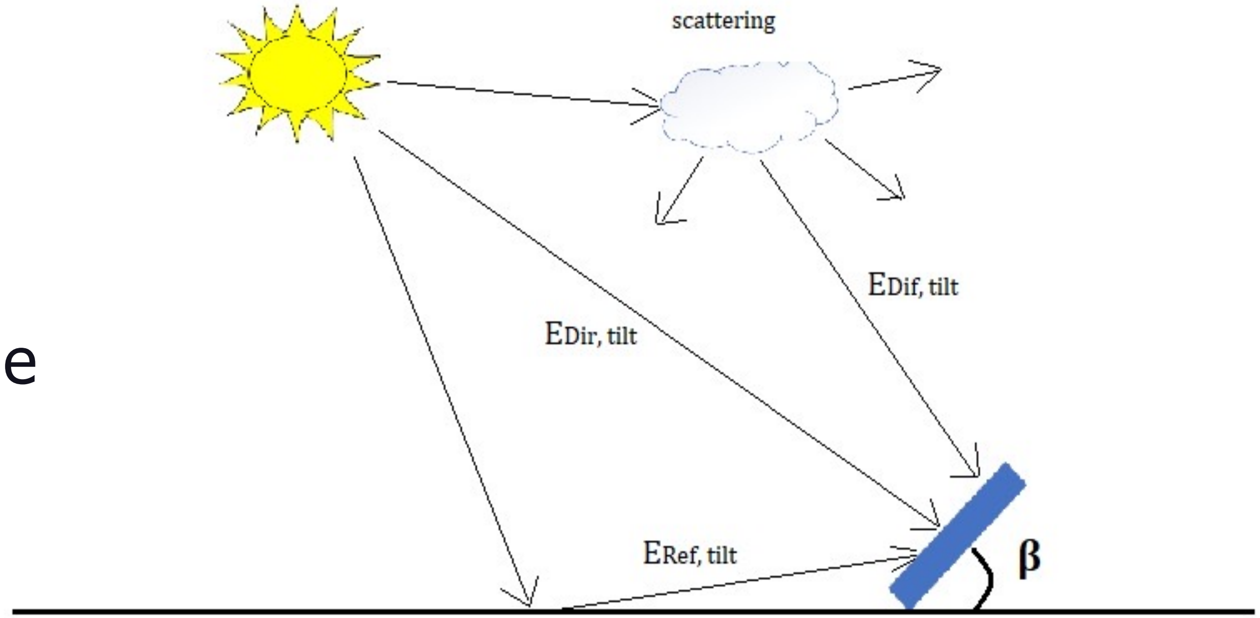


Figure 3-7: Components of incident radiation on a tilted surface.

Solar Radiation

Radiation on Tilted Surfaces

- Power on the horizontal surface A_{Hor}

$$P = E_{Dir,H} * A_{Hor}$$

$$P = E_{Dir,H} * A_{Hor} = E_{Dir,Vertical} * A_{Ver}$$

$$A_{Ver} = A_{Hor} * sin\alpha_S$$

$$A_{Ver} = A_{Pan} * sin\chi$$

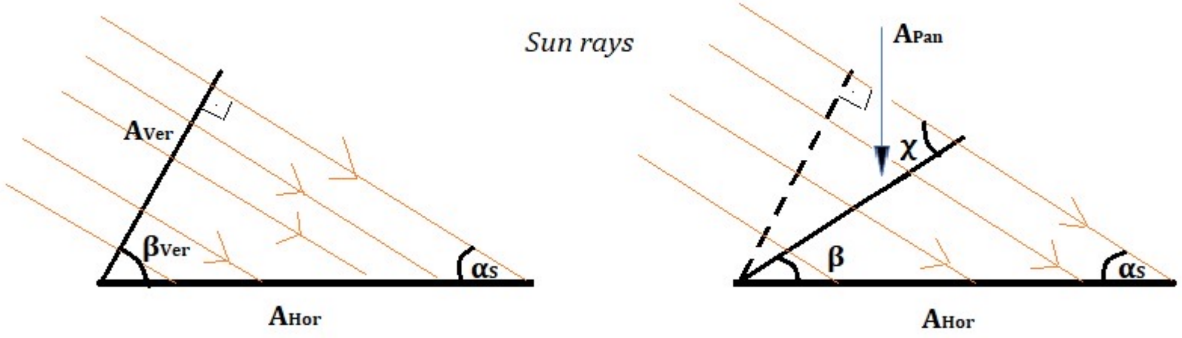


Figure 3-8: Direct radiation on a solar panel surface at two different tilt angles.

- Angle χ is complementary to inclination angle β
- α_S, solar altitude

- Direct radiation on tilted surface

$$E_{Dir,Gen} = E_{Dir,H} * \frac{sin(\alpha_S + \beta)}{sin\alpha_S}$$

Solar Radiation

Radiation on Tilted Surfaces

- Isotropic assumption for the calculation of diffused and reflected radiations
- Diffused radiation on a tilted surface $$E_{Dif,Gen} = E_{Dif,H} * \frac{1}{2}(1 + cos\beta)$$
- Reflected radiation on a tilted surface $$E_{Ref,Gen} = E_G * \frac{1}{2}(1 - cos\beta) * ALB$$
- E_G: global radiation on the ground
- ALB: ground albedo.

Energy conversion in solar cells

Physics of Semiconductors

- Electrons orbit around nucleus in specific shells, K(n=1), L(n=2)…n: principal quantum number
- Electron can jump between shells with absorption/emission of energy (photon)

$$\Delta E = \left|E_{after} - E_{before}\right| = h * \nu = h * \frac{c_0}{\lambda}$$

- h: Planck's constant = $6.6*10^{-34}$ Wsec^2
  v: radiation's frequency
  λ: wavelength
  c_0: light speed in a vacuum = $3*10^8$ m/sec.

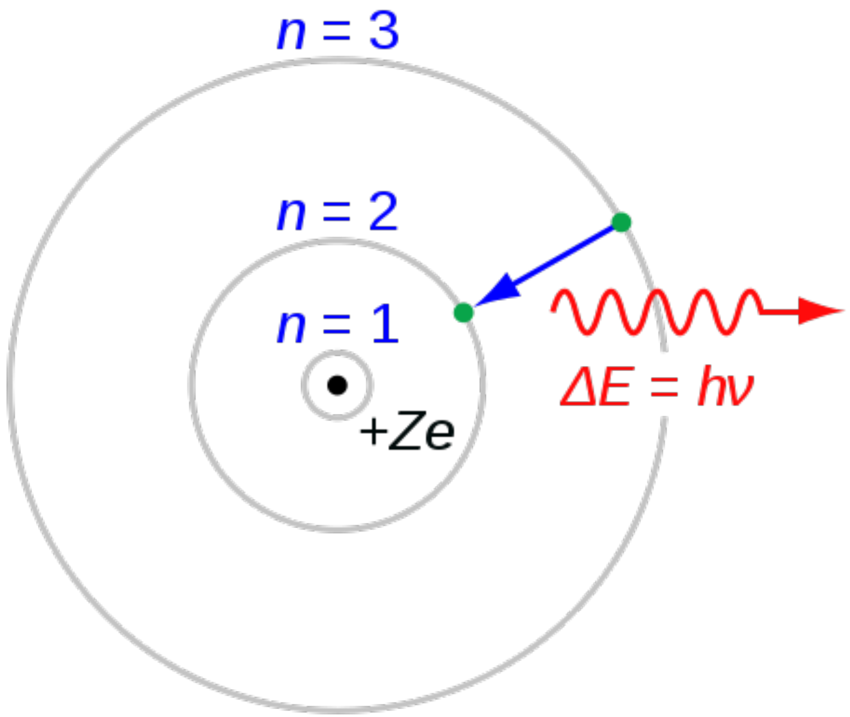


Figure 3-9: Bohr's atomic model.

Energy conversion in solar cells

Physics of Semiconductors

- Electrons of outermost shell are valence electrons
- Silicon has 4 valence electrons
- Valence band: highest energy band occupied by electrons
- Conduction band: first energy band empty
- Electrons need energy to overcome the band gap, to get from the valence to the conduction band

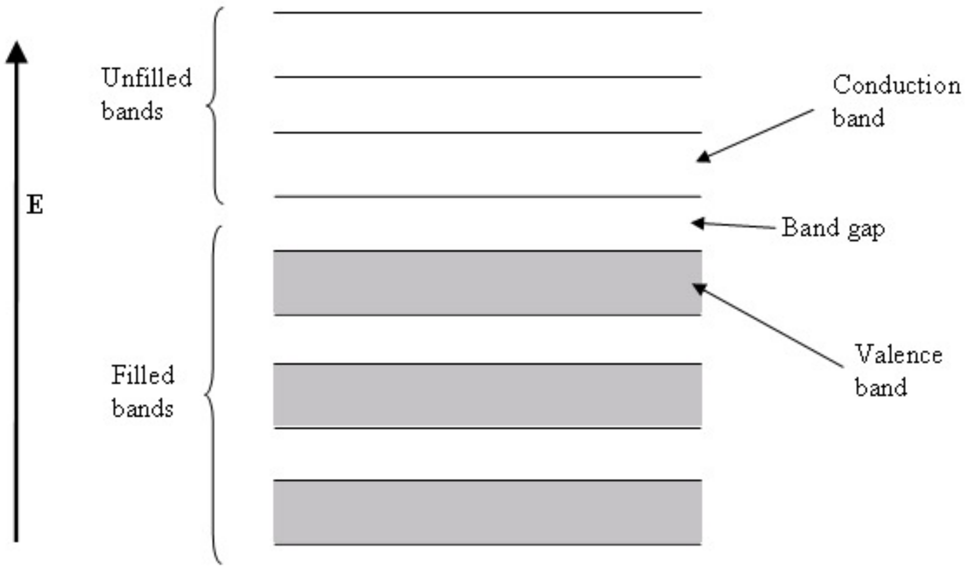


Figure 3-10: Band structure of a semiconductor.

Energy conversion in solar cells

Physics of Semiconductors

- A silicon crystal has band gap = 1.2 eV
- In absolute zero electrons remain in valence band
- Increase of temperature to start conductivity in a semiconductor
- Electrons in conduction band are considered free electrons and increase the crystal’s conductivity
- Semiconductors have band gaps 0-3 eV
- Insulators band gaps >3 eV
- In metals valence and conduction bands overlap

Energy conversion in solar cells

Doping of Semiconductors

- Intrinsic carrier concentration: the average electron-hole pairs in the crystal at any time
- Electron-hole pairs generated and recombined continuously
- Doping with foreign atoms to increase conductivity
- N-doping to increase free electrons (phosphorus)
- P-doping to increase number of holes (boron)

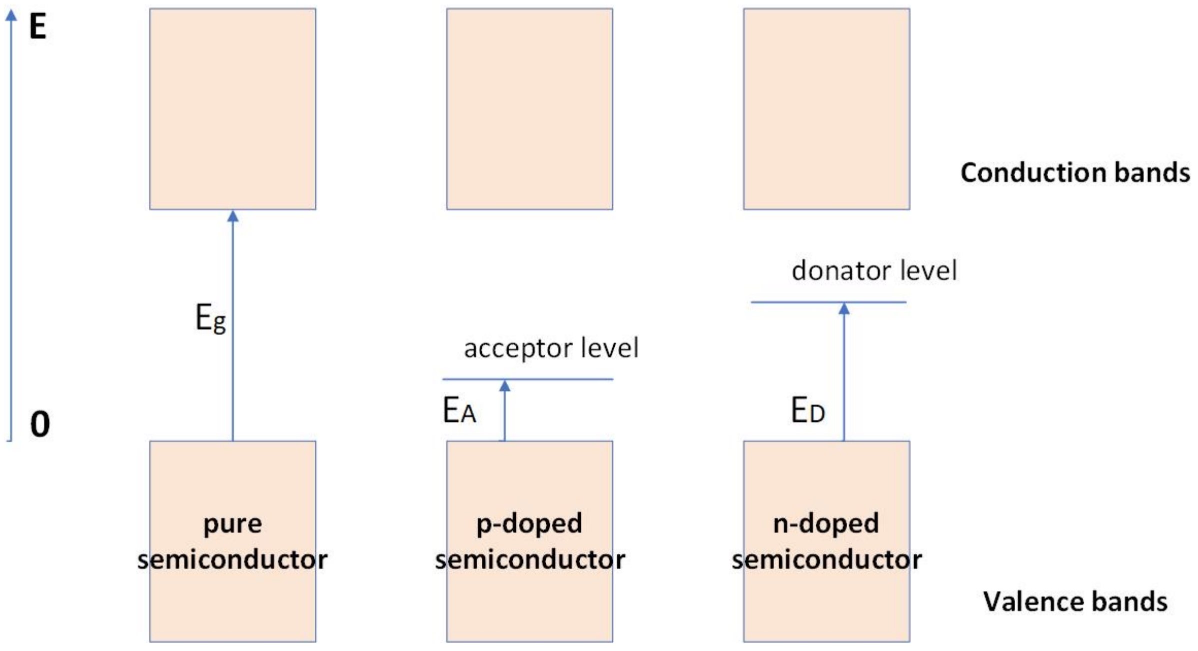


Figure 3-11: Energy bands in a pure, p-doped and n-doped semiconductor.

Energy conversion in solar cells

The p-n junction

- p-n junction, the boundary between p-type and n-type semiconductor
- At the junction free electrons of n-type diffuse to p-region and holes of p-type diffuse to n-region to recombine
- A region near the junction at the n-type becomes +charged, vice versa at the p-type
- Electric field formed that pushes electrons to the right, holes to the left, counteracting the diffusion process
- After balance, there’s a space charge region at the junction, causing a potential difference

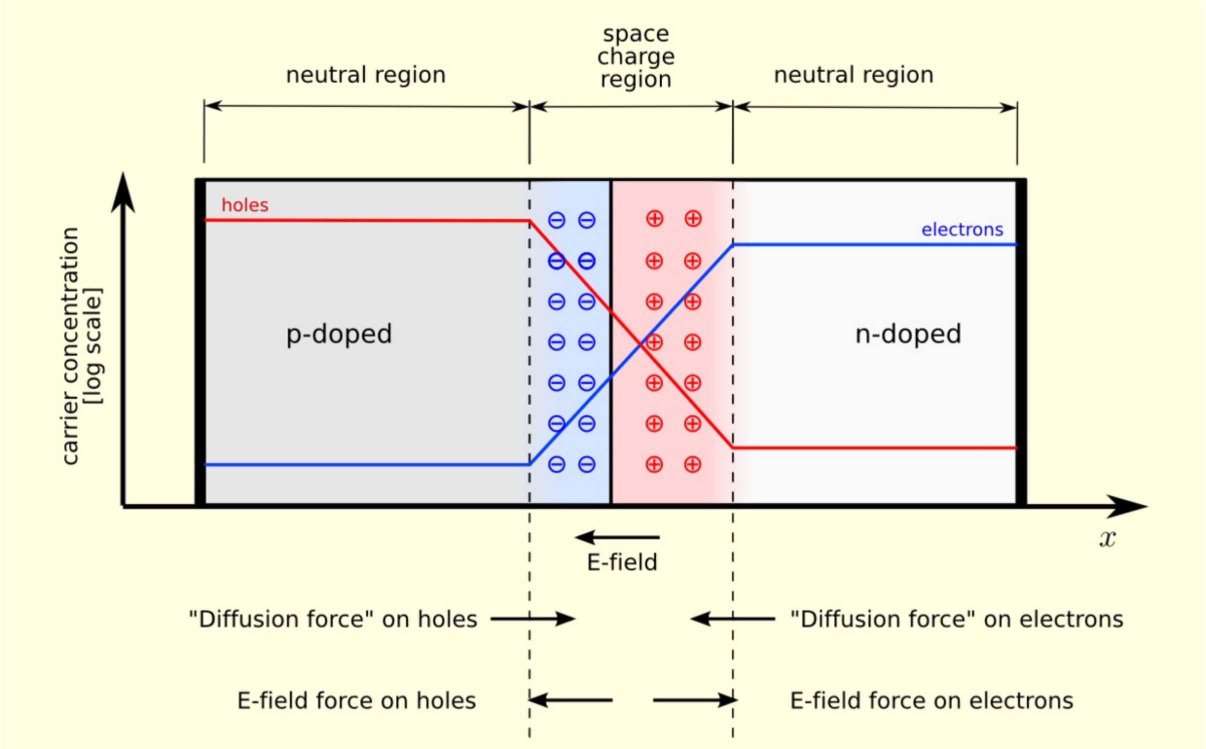


Figure 3-12: P-n junction diagram.

Energy conversion in solar cells

The p-n junction

- Voltage can be applied
- Forward bias voltage (p-type with +terminal): electrons and holes pushed towards junction, width of space charge area decreases, increase voltage until space charge region disappears and current begins to flow
- Reverse bias voltage (p-type with -terminal): width of space charge region enlarged, little current through the junction, increase voltage leads to breakdown and current begins to flow

Energy conversion in solar cells

Light and Semiconductors

- Radiation through semiconductor, energy decreases $E(x) = E_0 * e^{-ax}$
- Indirect band gap: min of conduction band and max of valence band have different crystal momentums, electron ca jump with photon and phonon participation
- Direct band gap: same crystal momentum, only photon participation

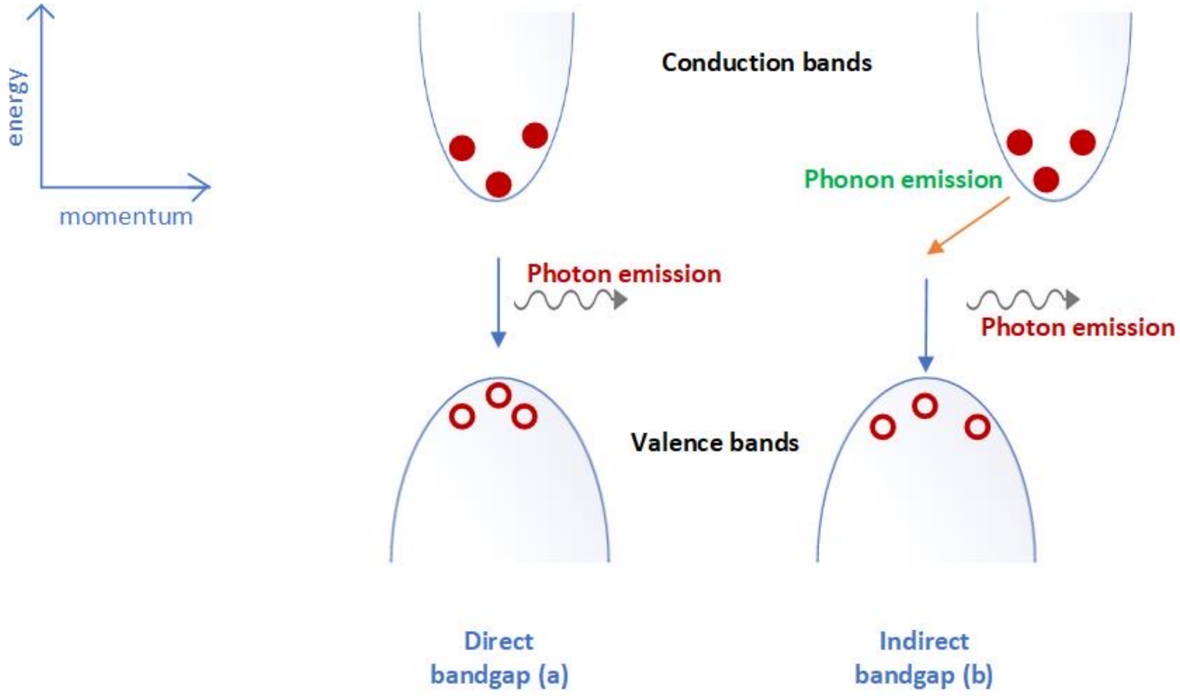


Figure 3-13: Photon emission in a direct and indirect semiconductor.

Energy conversion in solar cells

Light and Semiconductors

- Indirect semiconductors have lower absorption coefficients
- Indirect semiconductors: crystalline silicon
- Direct semiconductors: amorphous silicon, cadmium telluride etc.
- In electron-hole pair generation there’s conservation of energy AND momentum

Photovoltaic Technologies

- Various photovoltaic technologies, depending on semiconductor material
- Solar cells can be single-junction or multi-junction cells
- First generation cells: crystalline silicon, c-Si (monocrystalline and polycrystalline)
- Second generation: thin film cells, including amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS) cells
- Third generation: dye sensitized cells (DSC), organic materials

Photovoltaic Technologies

Crystalline Silicon

- Quartz reacts with carbon at >1900°C to produce metallurgical silicon (2% impurities)
- Metallurgical silicon + hydrochloric acid → trichlorosilane (SiHCl3)+hydrogen
- SiHCl3 distilled repeatedly
- Liquid SiHCl3 converted to solid polysilicon, two methods: Siemens process and Fluidized Bed Reactor

Photovoltaic Technologies

Crystalline Silicon

- Siemens process: SiHCl3 and hydrogen pass through chemical vapor deposition reactor at 1000-1200°C, SiHCl3 decomposes and silicon is deposited on thin silicon rods of high purity, placed in reactor and highly purified polysilicon is produced
- Fluidized bed reactor: silane+hydrogen gases injected in reactor bottom and a bed of small silicon seed granules become fluidized. Silane decomposes and silicon is deposited on the seeds which grow
- Polysilicon further processed for use in solar cells

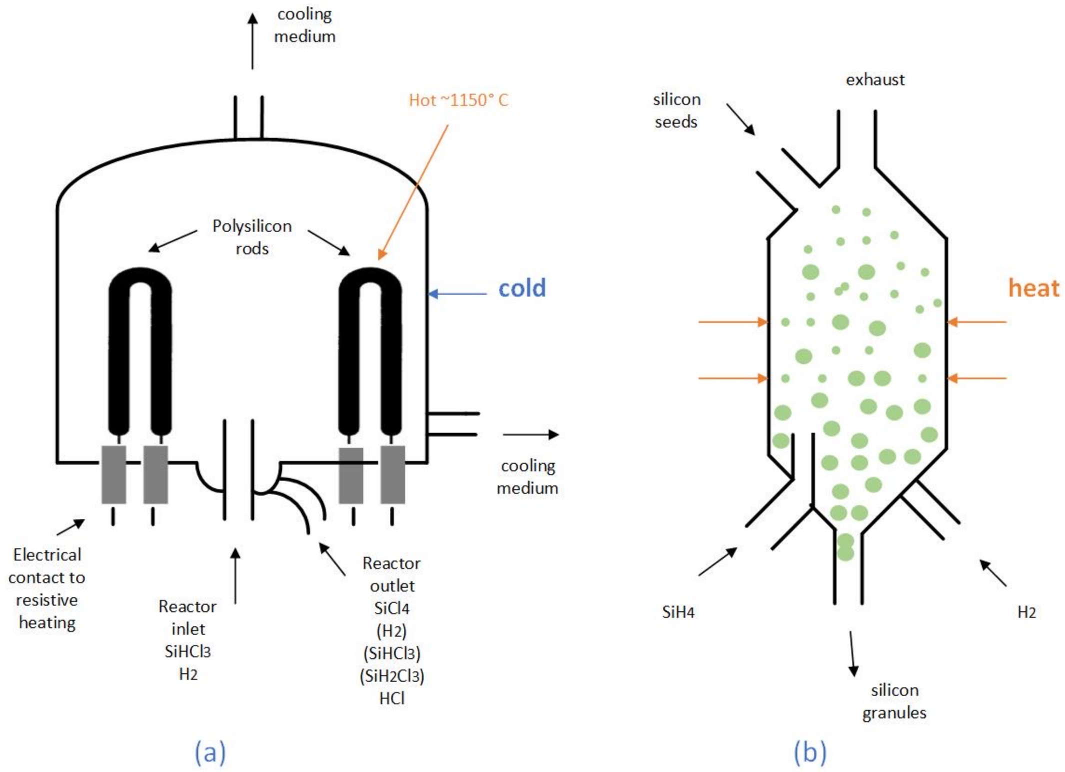


Figure 3-14: Illustration of the Siemens (a) and Fluidized Bed Reactor (b) processes for the purification of silicon.

Photovoltaic Technologies

Crystalline Silicon

Monocrystalline

- Czochralski method for production of monocrystalline silicon from polysilicon
- Highly purified silicon is melted in a crucible at ~1400°C
- A rod-mounted seed crystal is dipped in molten silicon and slowly pulled upwards while rotated
- Fluid silicon gets attached to rod and crystallizes
- Temp, rate of pulling, rotation speed controlled to adjust thickness of monocrystalline silicon rod
- Rods produced with diameter up to 30cm and length up to 2m

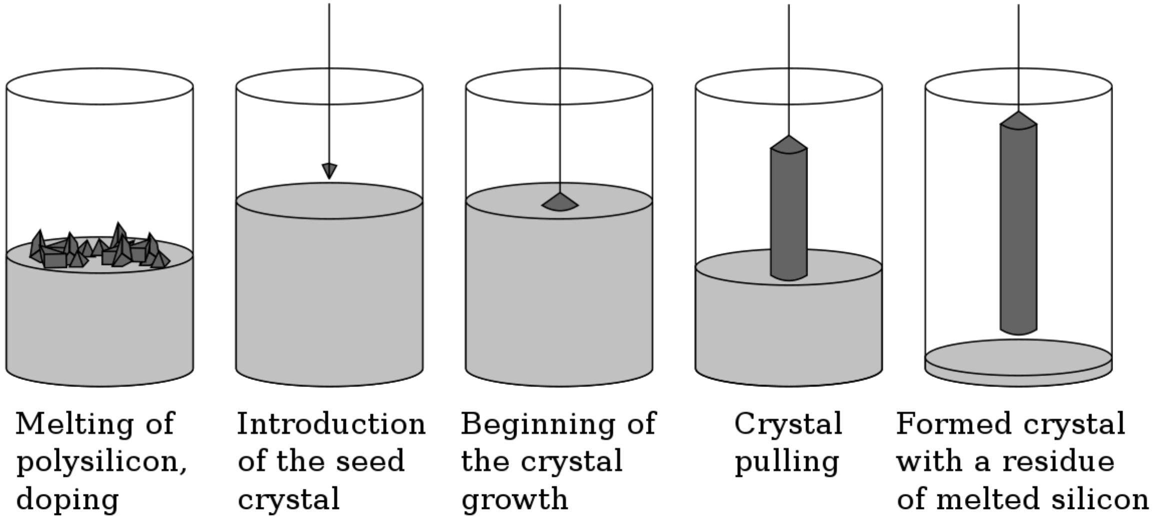


Figure 3-15: The Czochralski process.

Photovoltaic Technologies

Crystalline Silicon

Monocrystalline

- Float Zone process, alternative method
- Seed crystal placed under vertical polysilicon rod
- An induction coil is slowly pushed from bottom upwards, melting silicon as it passes
- The monocrystal is formed from bottom upwards
- Any impurities are driven upwards, highly crystal quality achieved
- More expensive than Czochralski process
- Monocrystalline silicon systems have great conversion efficiency, 18-22%, higher in labs, high manufacturing costs, require perfect crystal structure

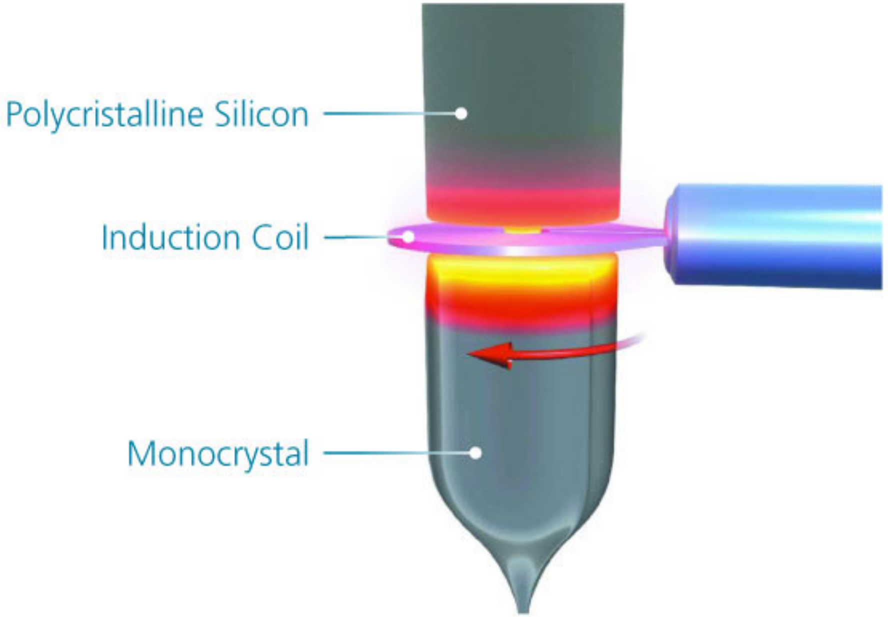


Figure 3-16: The Float Zone process.

Photovoltaic Technologies

Crystalline Silicon

Multicrystalline

- Multicrystalline silicon 2-3% lower efficiency than monocrystalline, lower production cost, crystal doesn’t need to have perfect structure
- Polysilicon pieces put into graphite crucible and melted using induction heating
- Crucible let to cool from bottom, as heating ring pulled upwards
- Small monocrystals formed on bottom, grow sideways until they meet. Column growth
- After melting completes, silicon block is cut into ingots

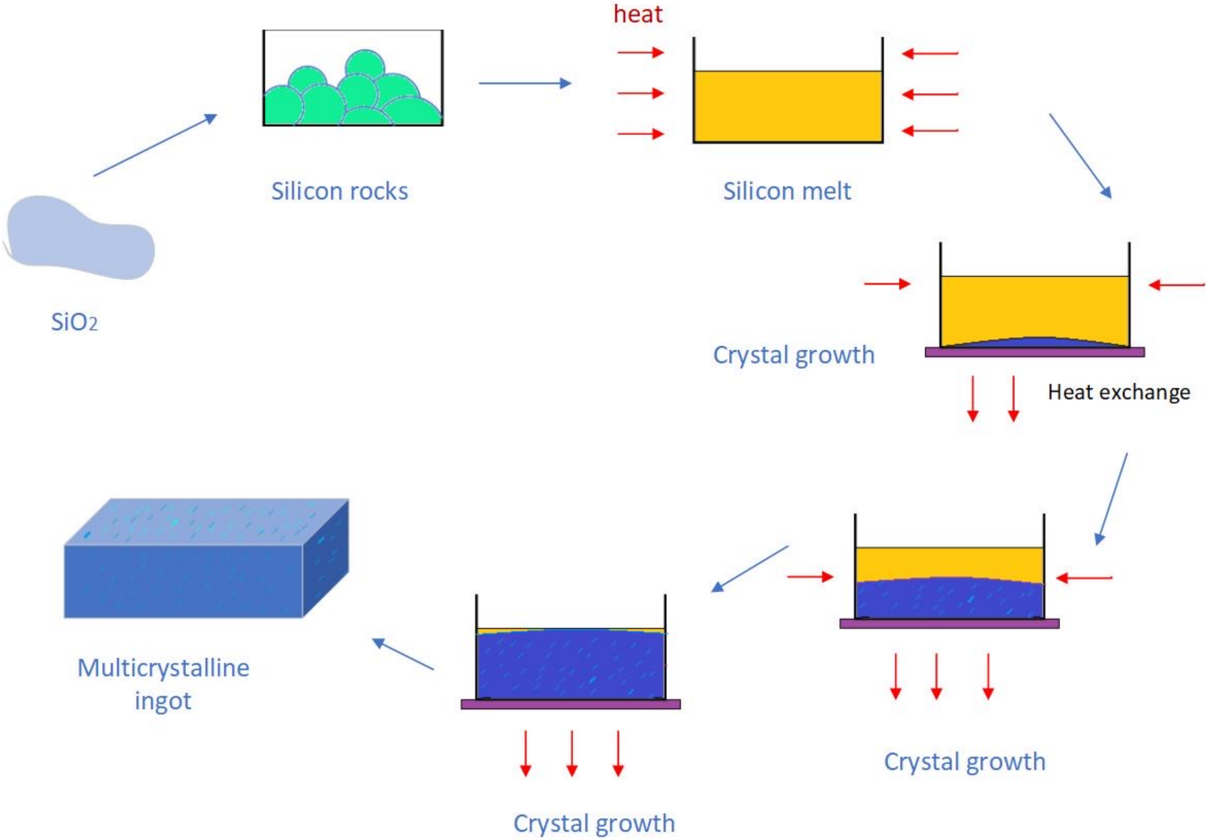


Figure 3-17: Multicrystalline ingot production.

Photovoltaic Technologies

Crystalline Silicon

Wafer production

- Ingots are cut into wafers, usually with wire saws
- Ingot is attached to a top plate and lowered through wire blades to cut into wafers
- Saw has hundreds up to thousand wires with diameter ~0.2mm, moving at high speed
- Slicing method can be fixed abrasive slicing or loose abrasive slicing

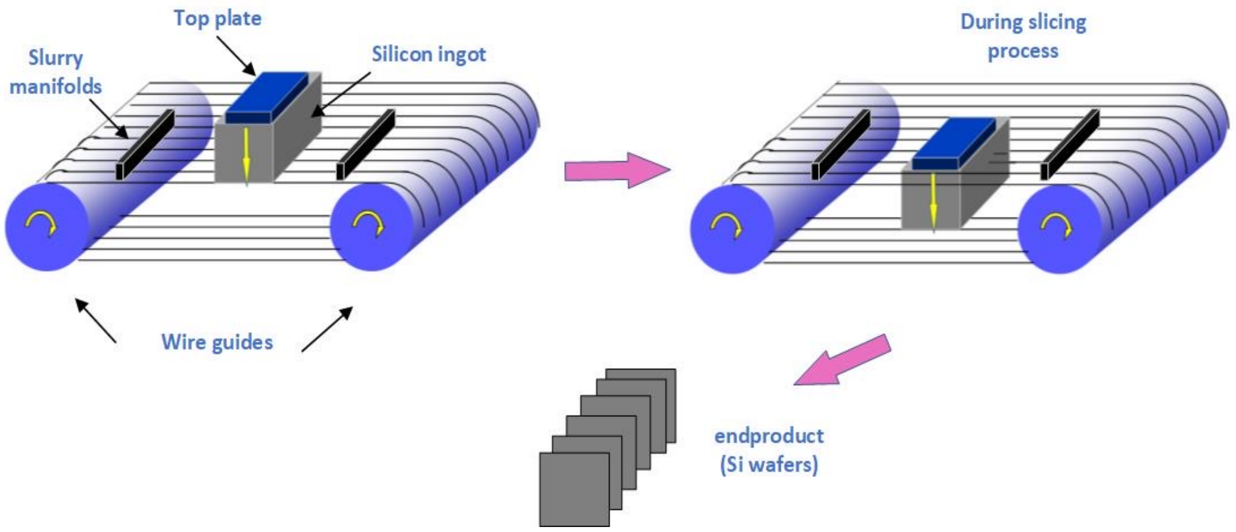


Figure 3-18: Wire saw wafer production.

Photovoltaic Technologies

Crystalline Silicon

- Fixed abrasive slicing: diamond abrasive particles are chemically bonded to wire, cut is made by pressing ingot against wire while coolant is applied
- Loose abrasive slicing: slurry, a suspension of abrasive particles (water, oil..) is applied to the wire and cut is made by the rolling motion of abrasive particles between wire and ingot
- Saw wire method: saw losses can be large
- In fixed slicing, possibility of cleaning silicon chips and using again

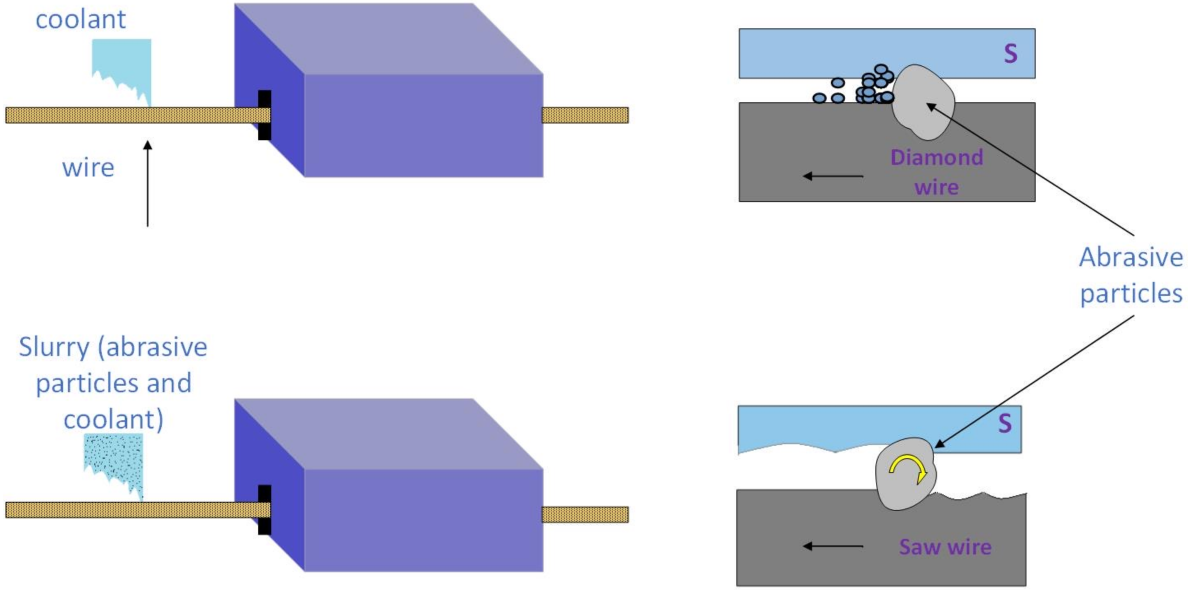


Figure 3-19: Fixed abrasive slicing (top) vs loose abrasive slicing (bottom).

Photovoltaic Technologies

Crystalline Silicon

- Another method to avoid saw losses is based on Edge-Defined Film-Fed Growth (EFG) process
- A thin sheet of silicon ribbon is pulled from a strip of molten silicon, formed by means of capillary force at the top of a graphite dye
- Another version is to pull the ribbon from an octagon-shaped gap, wafers are then cut from octagon sides with lasers

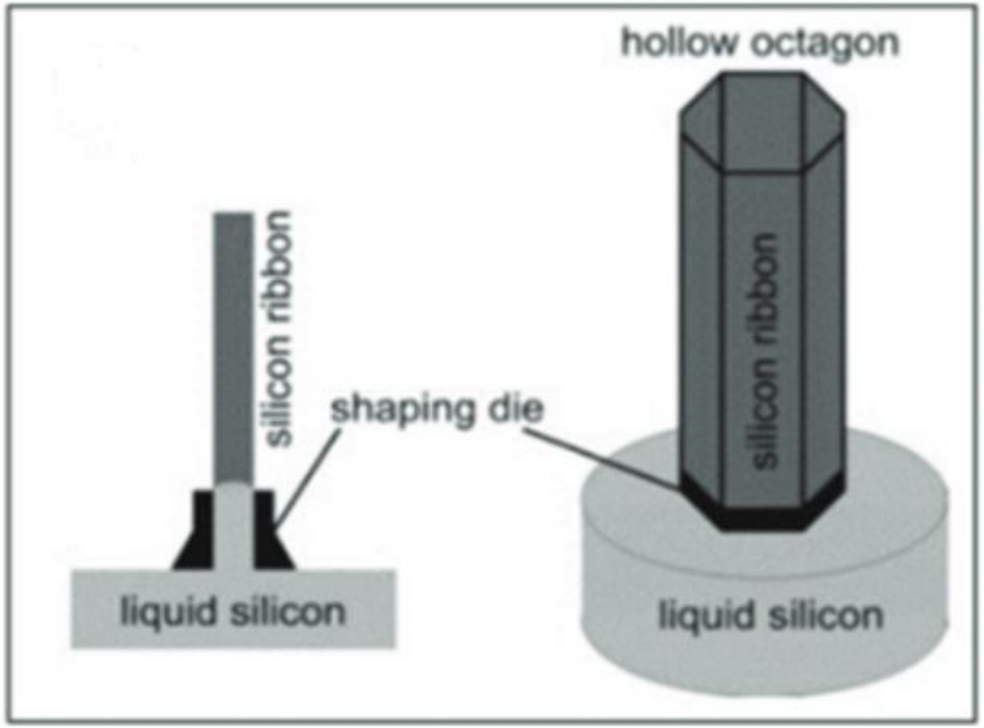


Figure 3-20: EFG method for wafer production (left) and growth of polygonal silicon ribbon based on EFG method (right).

Photovoltaic Technologies

Crystalline Silicon

- The wafers, which are doped, are dipped into an etching bath to remove contaminants or damage to crystal surface
- Texturizing of surface, for example with etching with potassium solvent
- Formation of p-n junction, with emitter diffusion method. P-doped wafers are given an n-type surface by diffusion with phosphorus source
- Phosphosilicate glass(PSG) forms, later removed
- Anti-reflection coating with deposition of silicon nitride coating

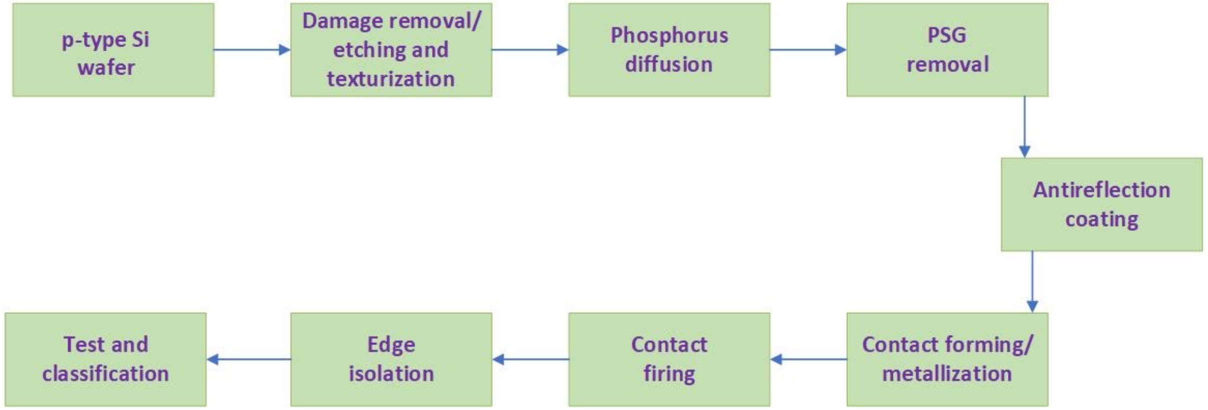
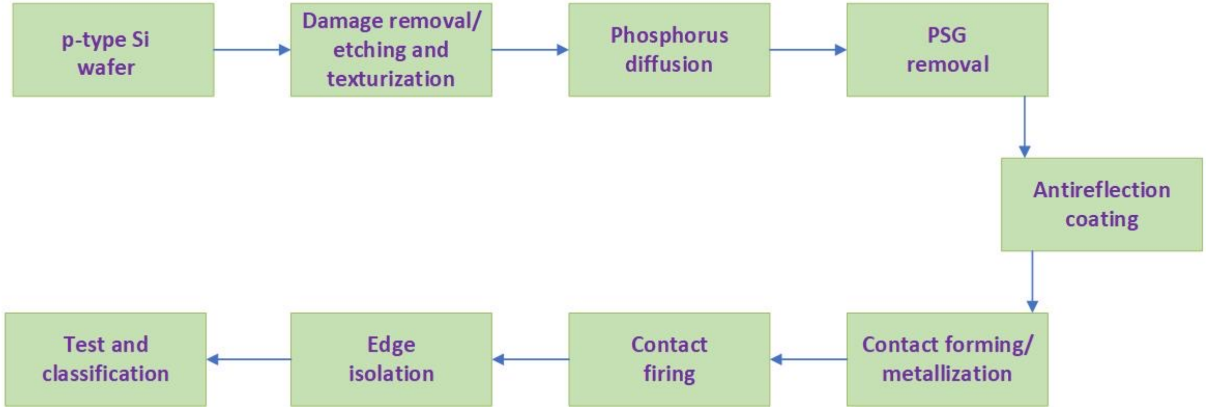


Figure 3-21: Standard crystalline silicon solar cell production steps.

Photovoltaic Technologies

Crystalline Silicon

- Contacts applied in the screen printing process. Mask with slits placed on cell, metal paste brushed on
- For rear side contacts, first soldering contact surfaces of silver paste applied and after rear side is covered with aluminum. Front side contacts applied
- Contact firing of cells to harden pastes, Al atoms diffused into base to generate p-layer for back surface field
- Edge isolation to clear wafer edges
- Testing of cell for classification



p-type Si wafer

Damage removal/ etching and texturization

Phosphorus diffusion

PSG removal

Antireflection coating

Contact forming/ metallization

Contact firing

Edge isolation

Test and classification

Figure 3-21: Standard crystalline silicon solar cell production steps.

Photovoltaic Technologies

Crystalline Silicon

- Solar module can have glass-foil or glass-glass structure
- Glass-glass structure: solar cells are sandwiched between glass on both front and back. Risk of cell breakage less than glass-foil. Cells are not so susceptible to shear stress. No metal frame

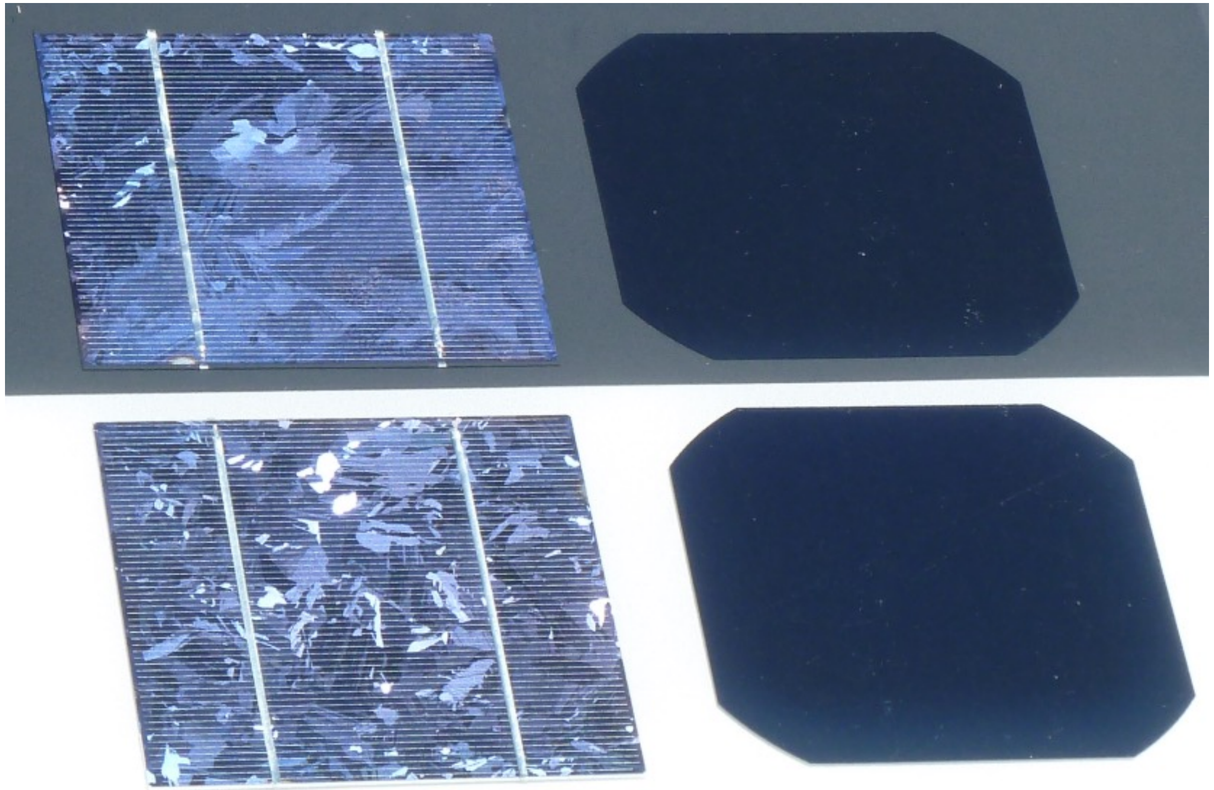


Figure 3-22: Comparison of multicrystalline (left) and monocrystalline silicon (right) solar cells.

Photovoltaic Technologies

Crystalline Silicon

Solar Module

- Glass-foil: cells are electrically connected in series with galvanized copper strings, forming cell strings
- Cell string situated between two EVA (ethylene-vinyl-acetate) or POE (polyolefin elastomer) transparent sheets
- Glass sheet on front side, foil on rear side
- Heating in vacuum, EVA material first softens and flows around cell, then hardens
- Rear side foil is electric insulator and protects from moisture. Usually a TPT made of polyvinyl fluoride and polyester films
- Module edges sealed before put into aluminum frame

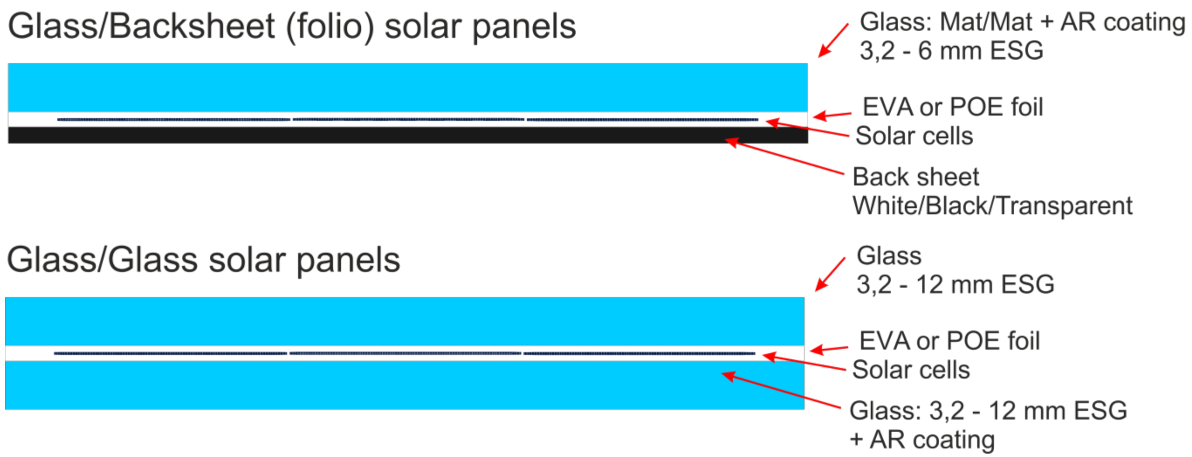


Figure 3-23: Glass-foil vs glass-glass solar module.

Photovoltaic Technologies

Amorphous Silicon

- Amorphous silicon is the non-crystalline form of silicon
- Most popular material in thin film technology
- Irregular structure, dangling bonds
- Hydrogen is added to passivate the material by bonding to dangling bonds, a-Si:H
- a-Si:H has direct band gap of 1.7-1.8 eV
- Absorption coefficient one or two factors higher than c-Si
- Sufficient radiation absorbed with cell thickness of 0.5μm

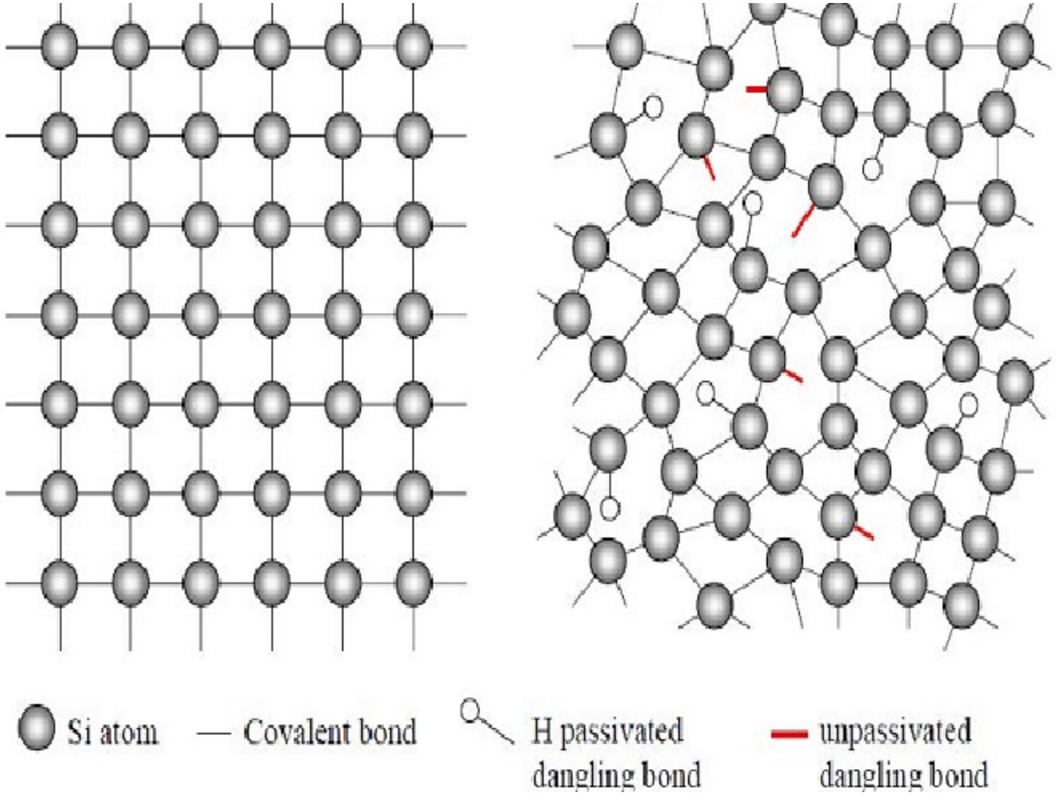


Figure 3-24: Structure of crystalline silicon (left) and hydrogenated amorphous silicon (right).

Photovoltaic Technologies

Amorphous Silicon

- Two methods for production: chemical vapor deposition (CVD) and plasma enhanced chemical vapor deposition (PECVD)
- PECVD: silane and hydrogen gases flow into process chamber (200°C) and enter strong high frequency field
- Field causes electrons acceleration, which cause separation of silane & hydrogen molecules by impact ionization
- Plasma formation of highly reactive ions, which react with substrate surface and settle on it. Layer of a-Si:H formed

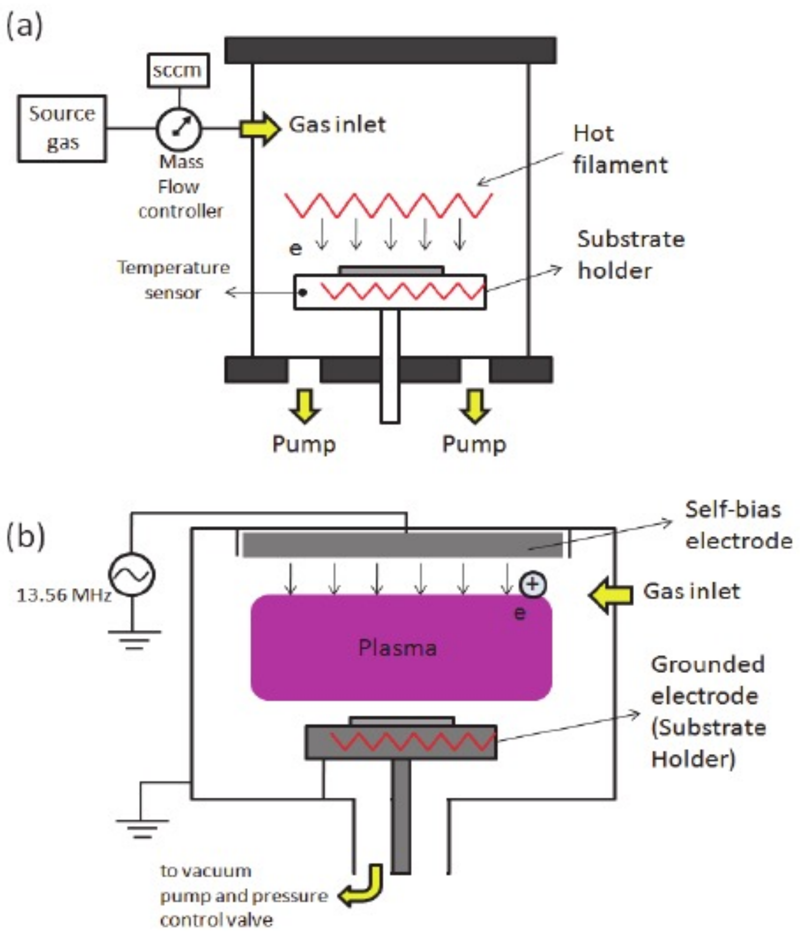


Figure 3-25: CVD (up) and PECVD (bottom) systems for thin film production.

Photovoltaic Technologies

Amorphous Silicon

- CVD: no plasma, higher temperature to achieve decomposition of gases (>450°C). Limited choice of substrate materials due to high temperatures
- Deposition rate around 0.2nm/sec
- a-Si:H layer with thickness of 0.5µm would take 40min to form
- New processes like Very-High-Frequency-PECVD and Hot-Wire-CVD promise to increase deposition rates

Photovoltaic Technologies

Amorphous Silicon

- structure of cell: glass sheet coated with a transparent electrode of conducting oxide (TCO)
- p, intrinsic and n-layer of a-Si:H
- Thin rear contact of silver or aluminum
- Total thickness less than 2µm
- Carbon added to p-layer to increase band gap, transparent layer
- Absorption happens in i-layer, strong electric field, from building up p-i-n cells, separates generated particles and transports them to designated areas, no time to recombine

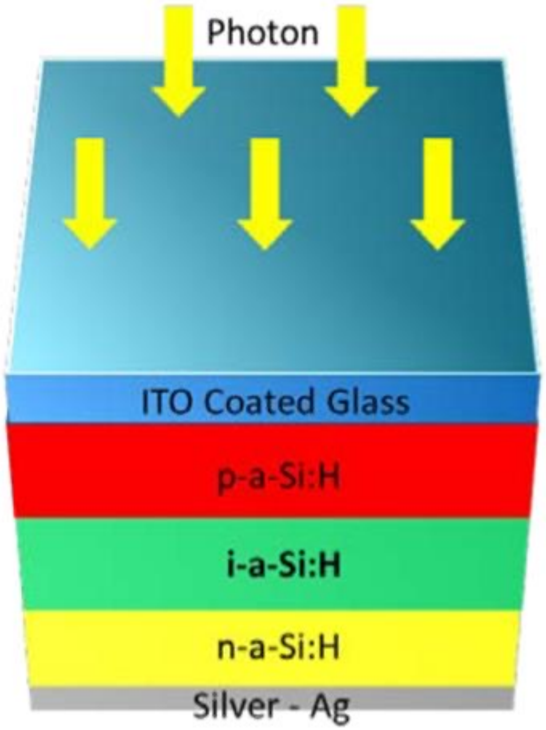


Figure 3-26: Structure of amorphous silicon thin film cell.

Photovoltaic Technologies

Amorphous Silicon

- Amorphous silicon cells have lower efficiencies than crystalline silicon
- Major drawback is light induced degradation, Staebler-Wronski effect
- Photoconductivity of a-Si:H reduced significantly under prolonged illumination, considered to be structure’s disorder fault
- Staebler-Wronski effect be reduced with increasing temperature or making the intrinsic layers thinner

Photovoltaic Technologies

Amorphous Silicon

Multi junction

- Tandem cell: two p-i-n cells stacked together to increase efficiency. Triple cells even better. Connection by electrically tunnel junctions
- Composite absorbing layer is formed with multiple band gaps, more efficient absorption of radiation
- Higher energy photons absorbed by wide band gap material (a-Si:H,1.8 eV). Lower energy photons absorbed in lower levels with narrower band gaps (a-Si:H, 1.6 and 1.4 eV)
- Band gap decreases from top to bottom
- Layers thickness selected to achieved current matching

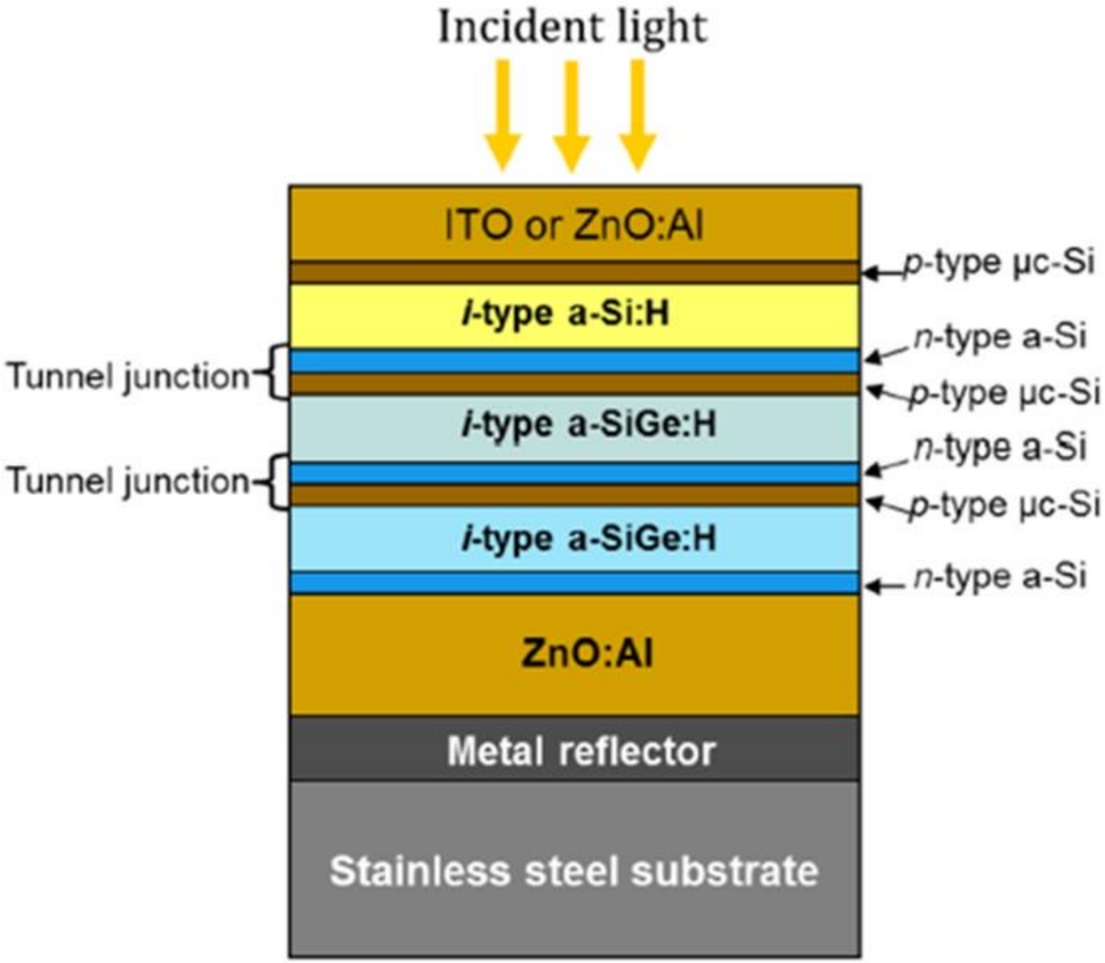


Figure 3-27: Structure of a triple-junction a-Si:H/a-SiGe:H/a-SiGe:H solar cell.

Photovoltaic Technologies

Amorphous Silicon

Micromorphous

- Micromorphous technology uses amorphous and microcrystalline silicon
- Microcrystalline Si is a-Si containing small crystals, similar behavior to c-Si, band gap of 1.12 eV
- Microcrystalline doesn’t show degradation, low absorption coefficient, thick layers needed
- Thin film solar cells can be connected to module during production. Interconnection process is embedded in cell manufacturing
- In wafer technology, cell manufacturing and series connection are separated processes

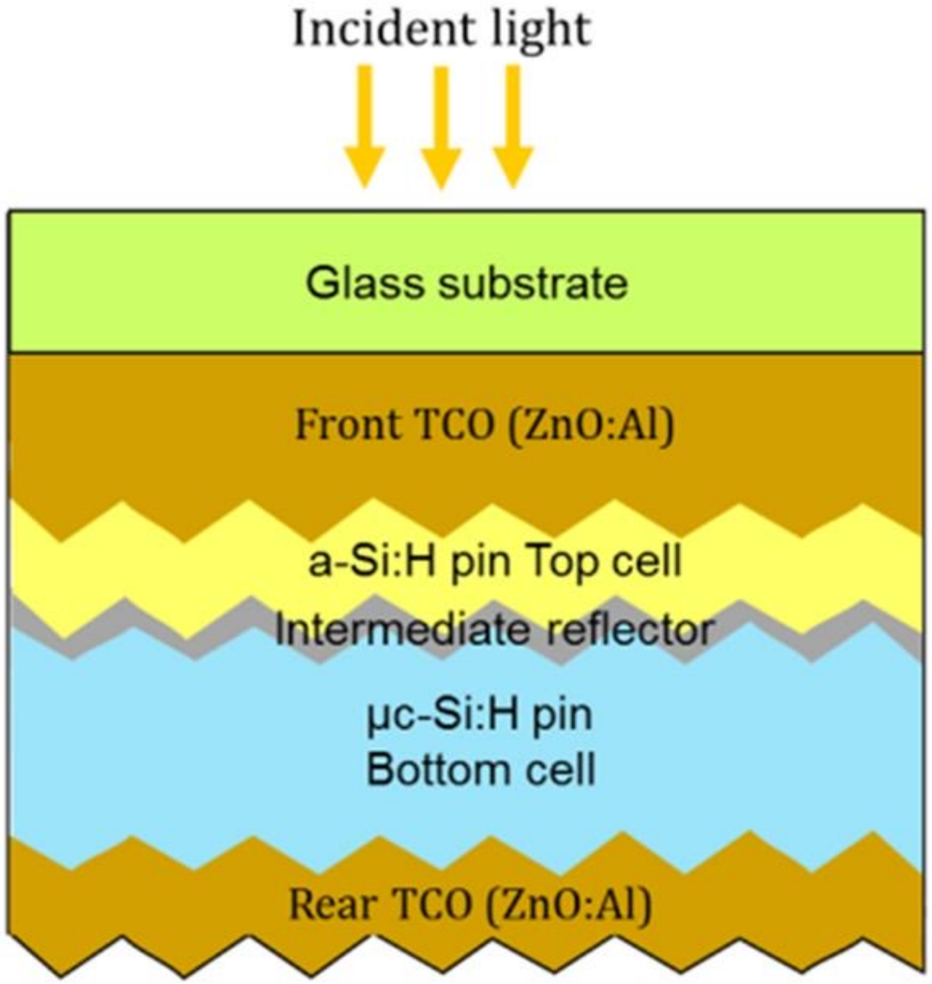


Figure 3-28: Structure of a micromorphous silicon solar cell.

Photovoltaic Technologies

Cadmium-Telluride Cells

- CdTe efficiency competes multicrystalline silicon
- Lower cost than c-Si technology
- CdTe is a direct semiconductor, band gap of 1.45 eV
- Deposition method is thermal evaporation over a short distance (Close-Spaced Sublimation, CSS): semiconductor vaporizes at 500°C and deposits on lower temperature substrate
- Structure: thin film of n-doped CdS + thicker absorbing layer of CdTe. Different band gaps. Thin coating with CdCl2 to increase efficiency
- Concerns: Toxicity of cadmium, availability of telluride

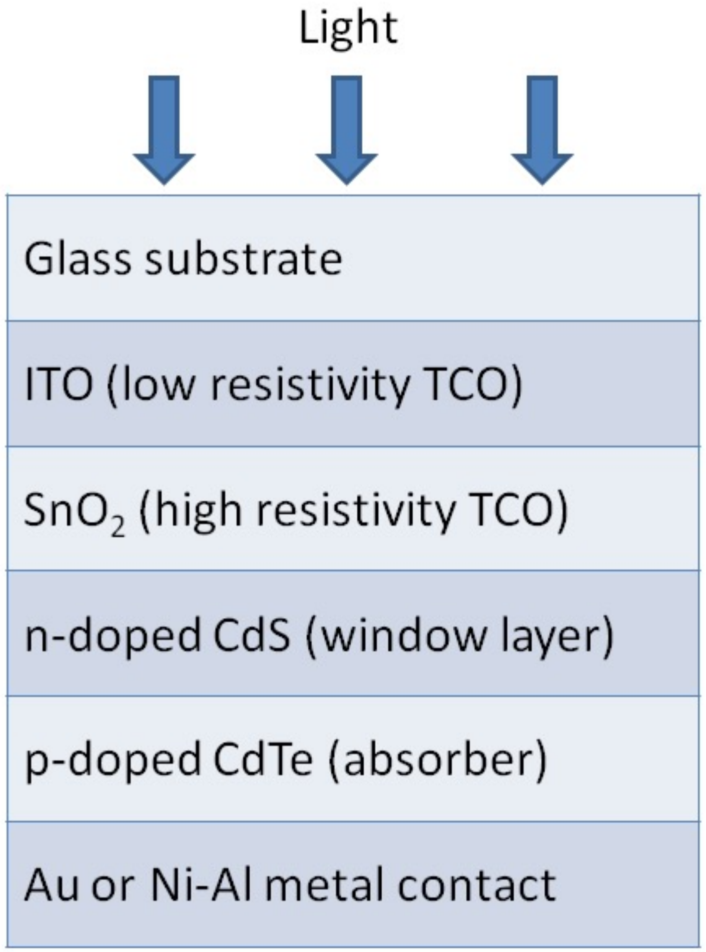


Figure 3-29: Structure of a CdTe solar cell.

Photovoltaic Technologies

CIGS Cells

- CIGS (copper-indium-gallium-selenide) is direct band gap semiconductor
- Molybdenum acts as rear electrode
- P-n junction is formed with a thin CdS layer and the thicker absorbing layer of CIGS
- Deposition by co-vaporization, individual elements vaporize at 500°C and are deposited on substrate
- CIGS has higher absorption coefficient than CdTe
- Highest potential, with produced efficiencies that compare to multicrystalline silicon cells

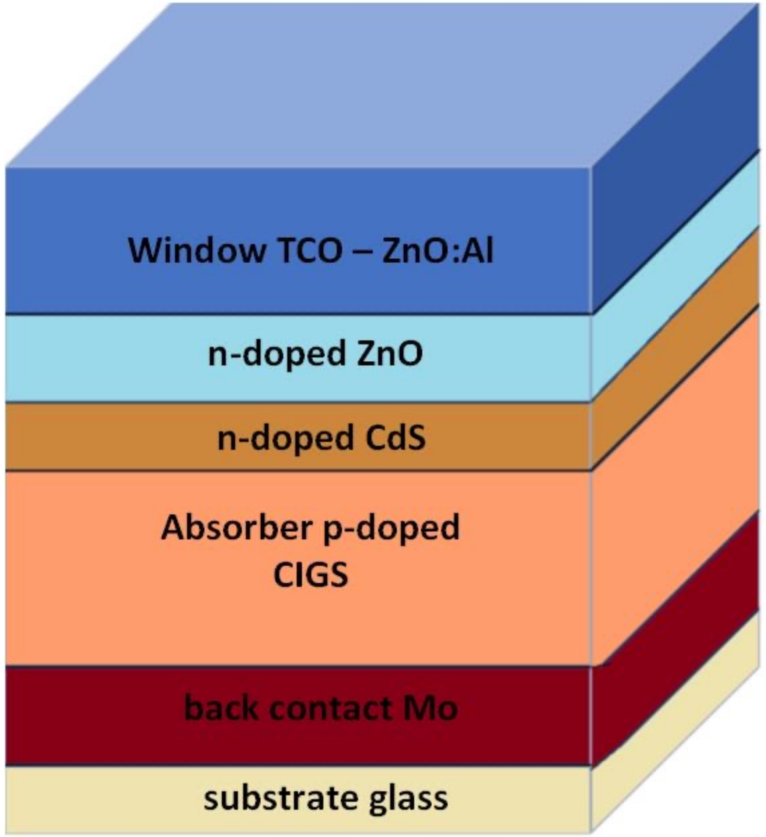


Figure 3-30: Structure of a CIGS substrate solar cell.

Photovoltaic Technologies

Hybrid Cells

- Hybrid cells: different materials on the basis of wafer cells for higher efficiencies
- HIT cell: crystalline and amorphous silicon
- Wafer is n-doped on both sides, an intrinsic layer with a p and n-doped a-Si:H deposited on each side. TCO layer also deposited on each side, along with metal strings
- Amorphous silicon layers act as effective surface passivation layers for c-Si wafer
- Lower temperatures needed for a-Si deposition
- Low cost alternative to traditional c-Si cells

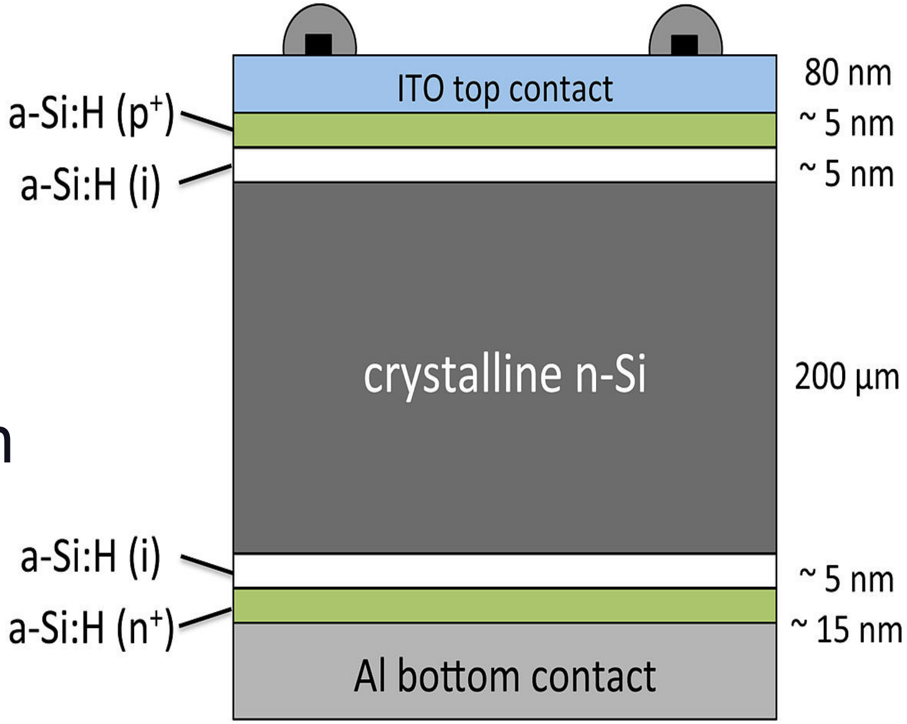


Figure 3-31: Structure of a HIT solar cell.

Photovoltaic Technologies

Hybrid Cells

- GaAs is direct band gap semiconductor with crystal structure
- High cost but high efficiency solar cells
- Monolithic stacking: upper and middle cells grow onto the bottom cell so the lattice constants of materials must be close to each other
- Mechanically stacked: different cells stacked mechanically on top of each other, materials can have different lattice constants

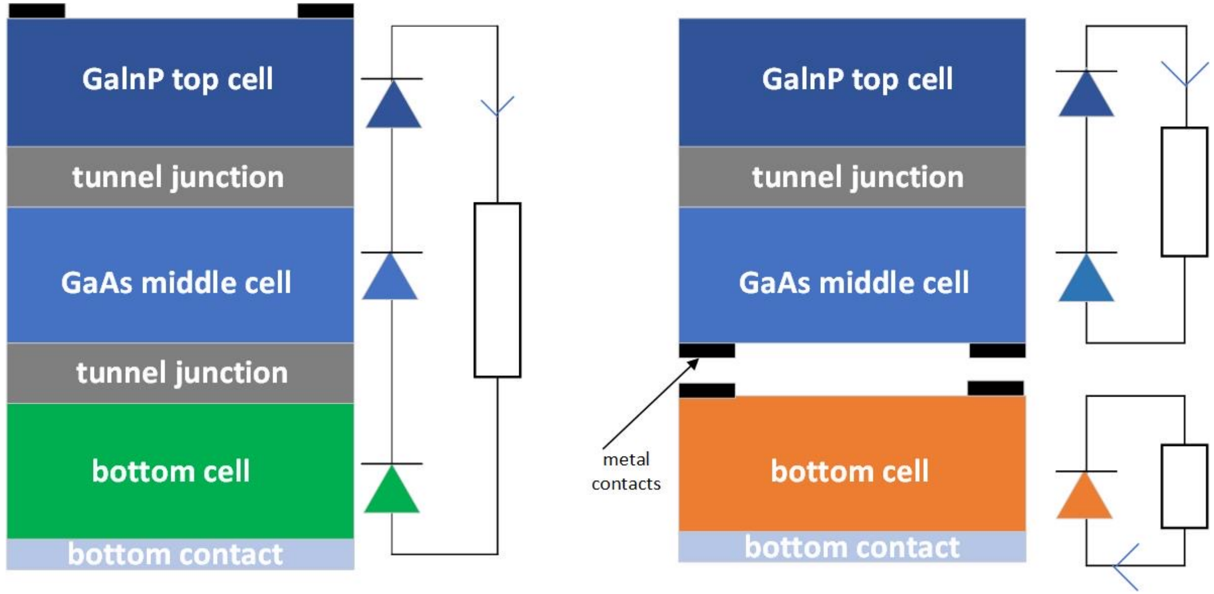


Figure 3-32: Structure of a monolithic (left) and a mechanically stacked (right) triple-junction cell.

- Cells don't have to be connected in series
- High efficiencies can be achieved

Photovoltaic Technologies

Other Cell Technologies

- Third generation cells include dye sensitized solar cell (DSC) and organic cells
- N-type DSC is most common type. Composed of a layer of titanium dioxide nanoparticles, covered with molecular dye that absorbs sunlight
- Titanium dioxide is submerged in an electrolyte solution, catalyst above based on platinum. DSC cells are low cost and stable over time
- Organic cell uses polymers as semiconductor material
- Composed of small molecules, like pentacene, polyphenylene vinylene, carbon based nanostructures etc.
- Less expensive than c-Si but lower absorption coefficient because organic cells have large band gap

- In this chapter, the solar spectrum was presented with the basics of the geometry of the Sun-Earth system. The fundamentals of energy conversion in photovoltaic solar cells were described and the main types of photovoltaic technologies were given.

Summary

Physics of sunlight and photovoltaics

Thank You

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Dr. Andreas Kazantzidis

Introduction to Renewable Energy

Lecture 4: Photovoltaic system components

IREEDER
Introducing Recent Electrical Engineering
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Section Outline

In this section, the components of a photovoltaic system are presented. The photovoltaic circuit is described and the power electronics of the system are visited. The types of photovoltaic systems and their design are given.

Section 1

Photovoltaic system components

This week's topics…

- Photovoltaic circuit
- PV power electronics
- Design of PV system
  - Stand-alone
  - Grid-connected
  - Hybrid

Photovoltaic circuit

Photodiode

- Photodiode, a p-n junction semiconductor that converts photons into electrical current
- Triangle represents p-region, arrows represent light
- Electron-hole pairs generated as photons absorbed when light hits semiconductor
- Diffusion force on electrons and holes, due to concentration gradient and force from electric field created near the junction

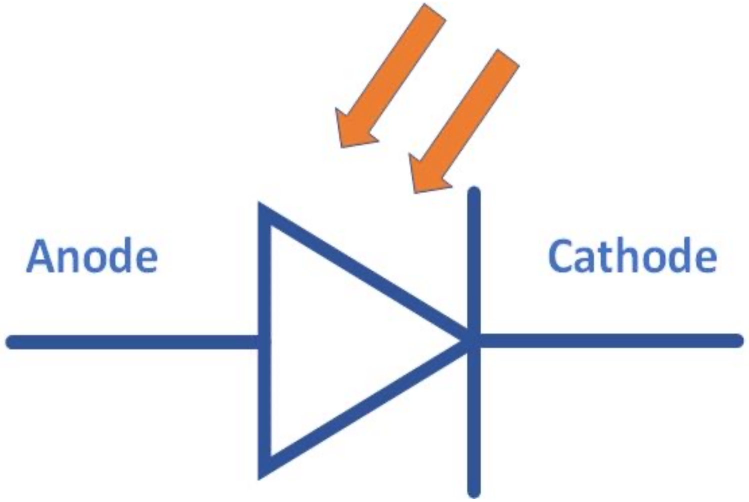

Figure 4-1: Photodiode symbol.

Photovoltaic circuit

Photodiode

- Photons absorbed near space charge region move to opposite directions due to electric field, don’t have time to recombine
- These moving charge carriers form the photocurrent I_{Ph}, which is proportional to irradiance E
- When no incident light, with a reverse voltage, there’s small reverse current flow, the dark current
- Dark current due to random electron-hole generation in space charge region

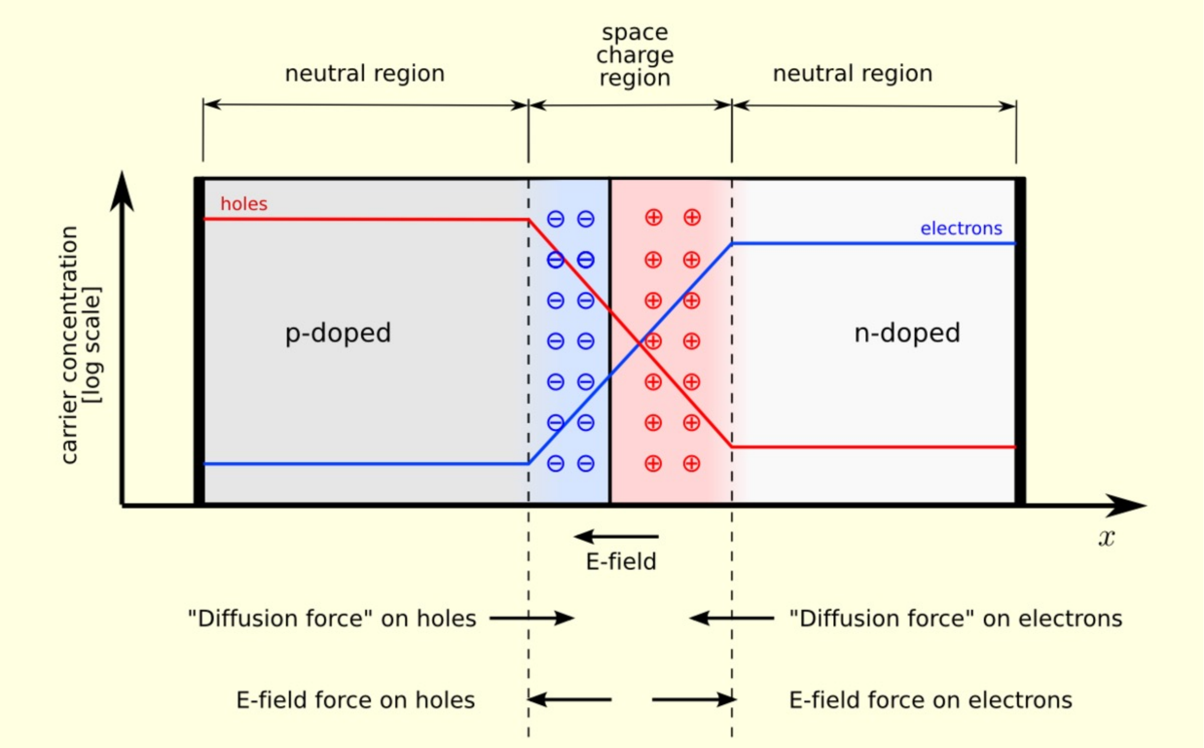

Figure 4-2: P-n junction diagram.

Photovoltaic circuit

Photodiode

- When zero bias or in photovoltaic mode, flow of photocurrent is restricted and voltage builds up
- The diode is then forward biased and dark current starts to flow in opposite direction of photocurrent
- Photovoltaic mode is preferred in low frequency or low light applications
- Photocurrent in photovoltaic mode shows little variation with temperature

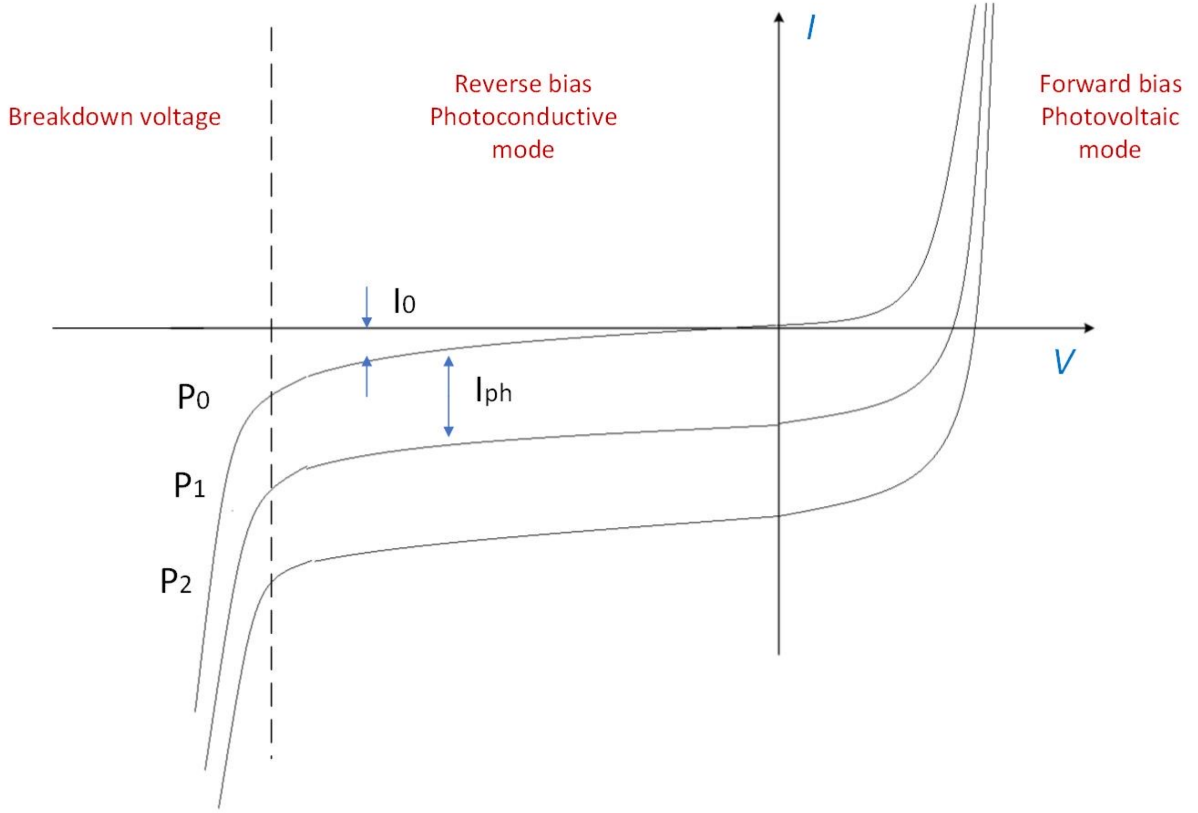

Figure 4-3: Photodiode mode of operation graph.

Photovoltaic circuit

Photodiode

- In photoconductive mode, photodiode is reverse biased, which causes the width of space charge region
- Larger area to absorb photons
- Reverse bias induces small amount of current, the saturation current, along its direction
- Photocurrent remains the same and is linearly proportional to irradiance
- Faster response times, increased noise
- When reverse bias reaches certain point, there’s sharp increase in current, breakdown voltage

Photovoltaic circuit

Equivalent circuit

- Solar cell can be represented by a current source and a diode
- Current represents generated current from incident radiation
- Diode represents p-n junction
- Resistances added to represent losses
- Series resistance R_S: losses in cell contacts and metal-semiconductor surface
- Shunt resistance R_{sh}: leak currents at cell edges and short circuits of junction
- Shunt resistance is the slope of the photodiode current-voltage curve for V=0

Photovoltaic circuit

Equivalent circuit

$$I = I_{Ph} - I_D - I_{sh} = I_{Ph} - I_S\left[exp\left(\frac{V_D}{m * V_T}\right) - 1\right] - \frac{V_D}{R_{sh}}$$

$$= I_{Ph} - I_S\left[exp\left(\frac{V + I * R_S}{m * V_T}\right) - 1\right] - \frac{V + I * R_S}{R_{sh}}$$

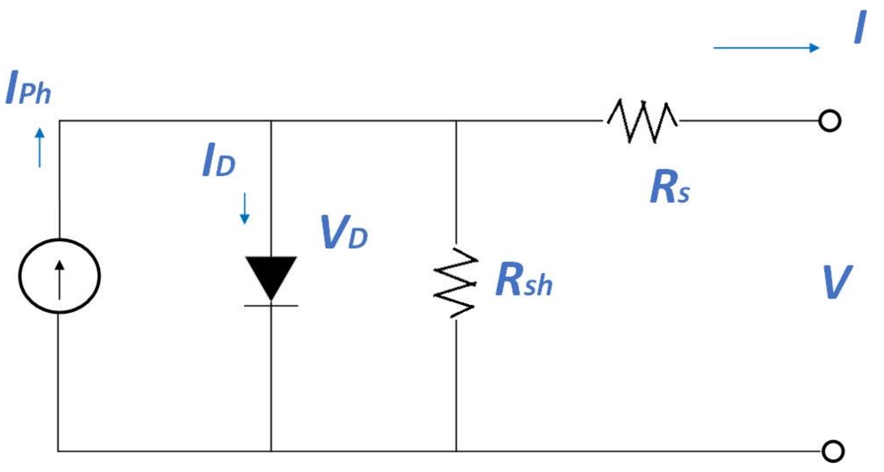

Figure 4-4: Solar cell equivalent circuit.

- I_{Ph}: photocurrent
- I_D: diode current
- I_{sh}: current flowing through shunt resistance
- I_S: reverse bias saturation current of the diode

Photovoltaic circuit

Equivalent circuit

- V_D: voltage across the diode
- m: ideality factor (deviation of the diodes from Shockley diffusion theory), $1 \leq m \leq 2$
- V_T: the thermal voltage of the diode, which depends on temperature T, the Boltzmann constant k, the number n of cells in series and the electron charge q.

$$V_T = \frac{n * k * T}{q}$$

Photovoltaic circuit

Equivalent circuit

- Short circuit current, I_{SC} is the current provided by the cell when it is short circuited, the voltage is zero.

$$I(V = 0) = I_{SC} = I_{Ph}$$

- In ideal solar cell, short circuit current is equal to photocurrent, hence proportional to irradiance
- Open circuit voltage, V_{OC} is the voltage when the current is zero and represents the maximum voltage available from a solar cell.

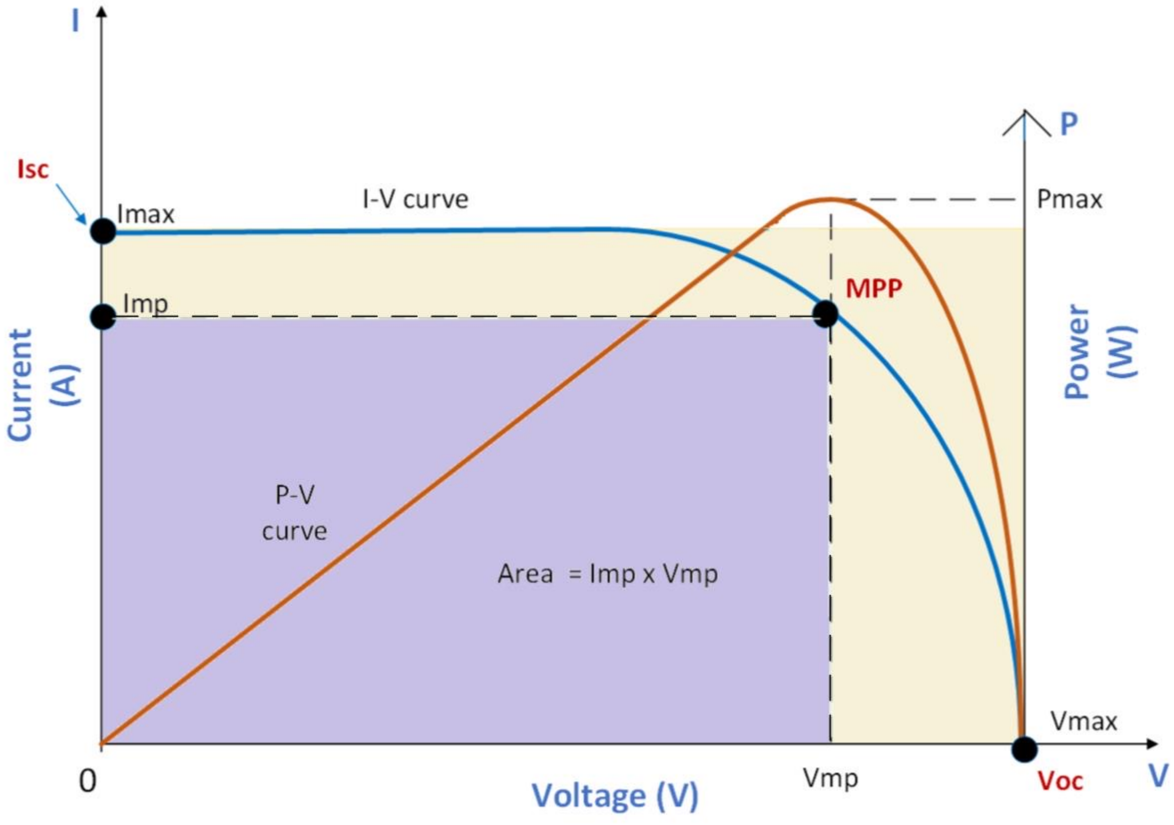

Figure 4-5: Characteristic current-voltage and power-voltage curves of a solar cell.

$$V_{OC} = V(I = 0) = m * V_T * ln\left(\frac{I_{SC}}{I_S} + 1\right)$$

Photovoltaic circuit

Equivalent circuit

- V_{OC} has lower dependency on irradiance than I_{SC}
- Maximum Power Point, MPP is the operating point at which the solar cell provides maximum power and corresponds to current I_{mp} and voltage V_{mp}.
- Maximum power corresponds to surface area I_{mp}*V_{mp}
- MPP varies depending on parameters like irradiance, temperature
- PV systems use methods to track MPP, to achieve maximum net power output

Photovoltaic circuit

Equivalent circuit

- Fill factor, FF determines maximum power of a cell with the help of V_{OC} and I_{SC}. It is the ratio of maximum power P_{MPP} to the product of V_{OC} and I_{SC}.

$$FF = \frac{P_{MPP}}{V_{OC} * I_{SC}} = \frac{V_{MPP} * I_{MPP}}{V_{OC} * I_{SC}}$$

- FF describes the quality of a solar cell. Silicon solar cells values between 0.75 and 0.85, thin film values between 0.6 and 0.75
- Approximation equation for FF:

$$FF = \frac{1 + ln\left(\frac{V_{OC}}{V_T} + 0.72\right)}{\frac{V_{OC}}{V_T} + 1}$$

Photovoltaic circuit

Equivalent circuit

- Efficiency, η, of solar cell represents the part of the optical power P_{opt} incident on the cell that is available as output electrical energy P_{MPP}. (A: cell area)

$$\eta = \frac{P_{MPP}}{P_{opt}} = \frac{P_{MPP}}{E * A} = \frac{FF * V_{OC} * I_{SC}}{E * A}$$

- Crystalline silicon cells have efficiencies between 15 and 22%

Photovoltaic circuit

Equivalent circuit

- Temperature increase of cell leads to increase in intrinsic carrier concentration
- Saturation current increases
- Reduction in open circuit voltage
- Temperature increase causes reduction of band gap, so short circuit current shows slight increase

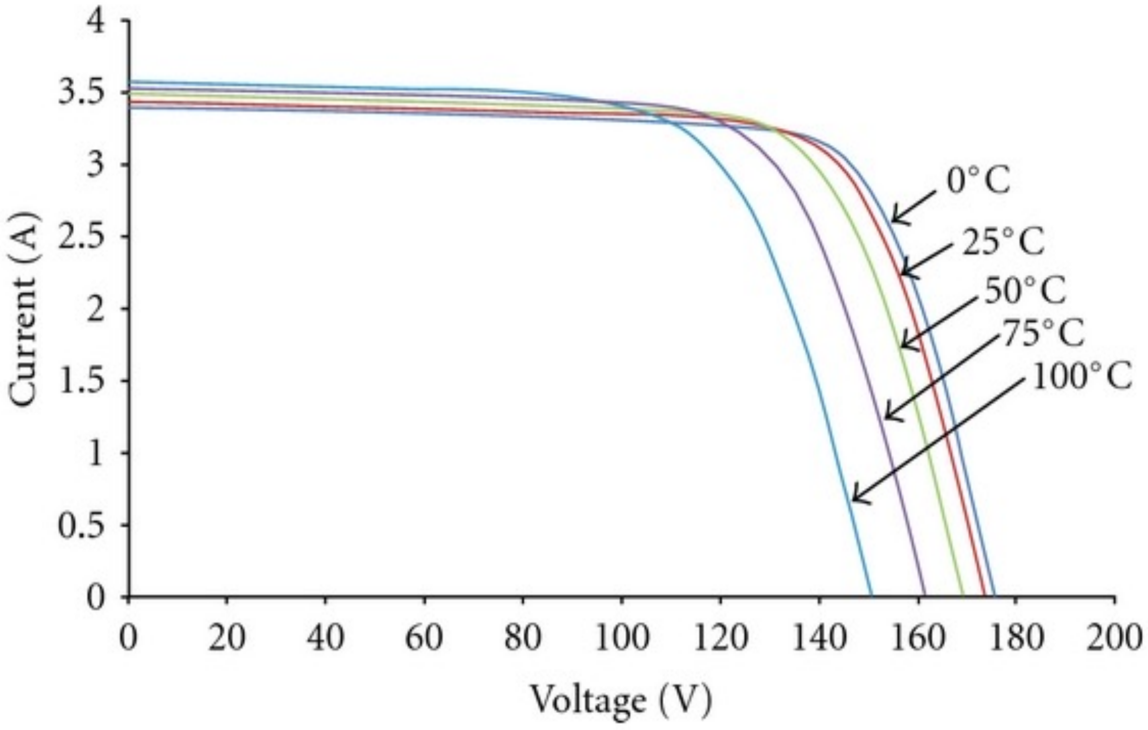

Figure 4-6: Temperature effect on I-V curve of solar cell.

Photovoltaic circuit

Equivalent circuit

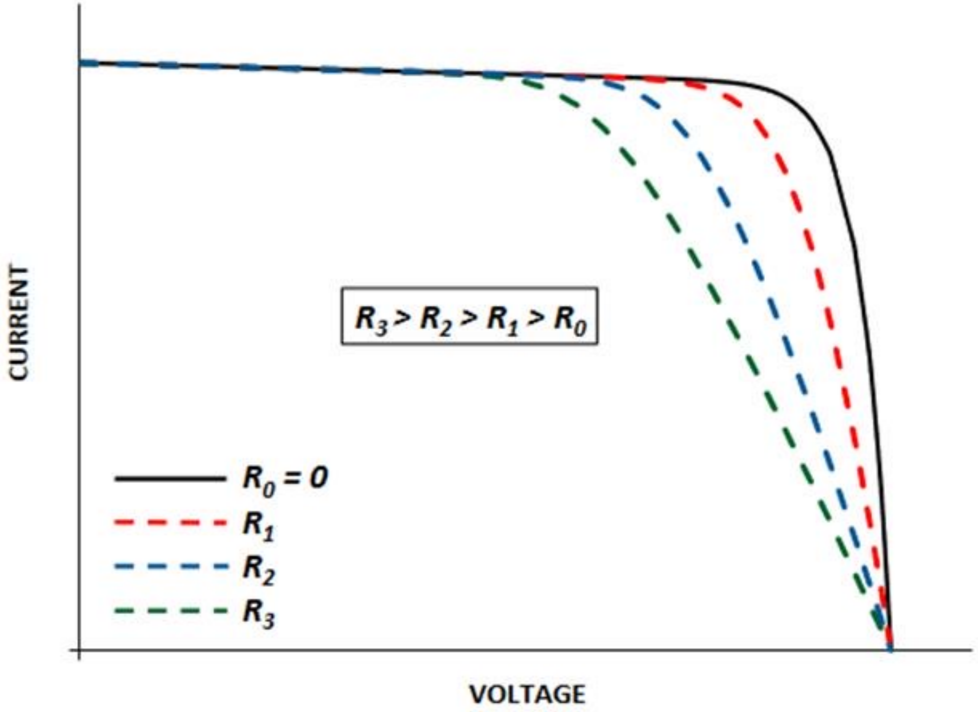

Figure 4-7: Effect of series resistance on I-V curve of solar cell.

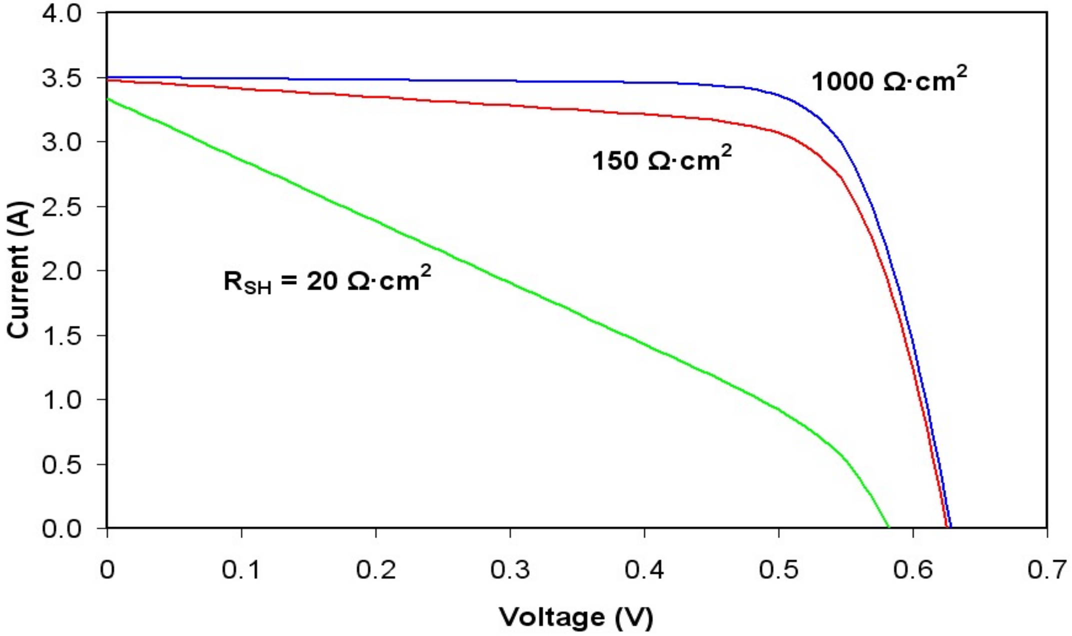

Figure 4-8: Effect of shunt resistance on I-V curve of solar cell.

- Series resistance increase leads to flattening of I-V curve and sinking of fill factor
- Similar effect has the reduction in shunt resistance
- As shunt resistance is reduced, shunt current increases. Very low values of R_{sh} lead to slight reduction in open circuit voltage

Photovoltaic circuit

Optical characteristics

- Spectral responsivity, R_λ of a cell, measures sensitivity to light. It shows the cell effectiveness in converting light power to electrical current. Varies with temperature, reverse bias and wavelength

$$R_\lambda = \frac{I_{Ph}}{P}$$

- Quantum efficiency, QE is the fraction of incident photons contributing to photocurrent. External QE_{ext} is the ratio of electron-hole pairs contributing to the photocurrent, N_{EHP}, to the number of photons incident on the cell, N_{Ph}.

$$QE_{ext} = \frac{N_{EHP}}{N_{Ph}}$$

Photovoltaic circuit

Optical characteristics

- Internal QE_{int} is similar but takes into account number of photons, not incident on cell, but absorbed by it. Losses due to reflection are not taken into account. It is defined by QE_{ext} and the reflection factor, R.

$$QE_{int} = \frac{Q_{ext}}{1 - R}$$

- QE is related to responsivity.

h: Planck constant

c: speed of light

q: electron charge

$$QE(\lambda) = \frac{R_\lambda}{\lambda} * \frac{hc}{q} = 1240 * \frac{R_\lambda}{\lambda}, \qquad W * nm/A$$

Photovoltaic circuit

Optical characteristics

- Spectral responsivity at low wavelengths is poor because high energy photons are absorbed only close to surface and many holes generated there recombine without contributing to photocurrent
- Mid-wavelengths: R_λ increases and approaches ideal
- Infrared: R_λ is reduced because absorption only takes place in lower cell layer. After certain wavelength, photon energy can't overcome band gap, curve collapses

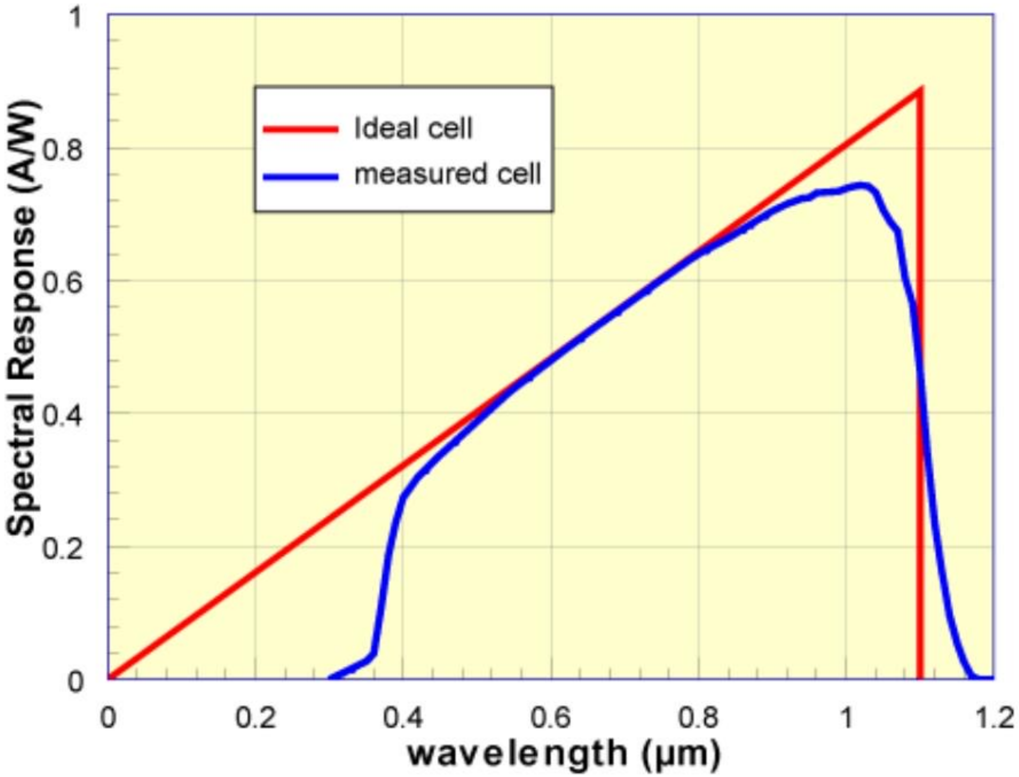

Figure 4-9: The spectral responsivity of an ideal and a measured solar cell.

Photovoltaic circuit

Two-diode model

- One diode circuit can't describe recombination in space charge region
- Two diode model represents real solar cells
- One diode with ideality factor=1, representing diffusion current
- Other diode with ideality factor=2, representing recombination current

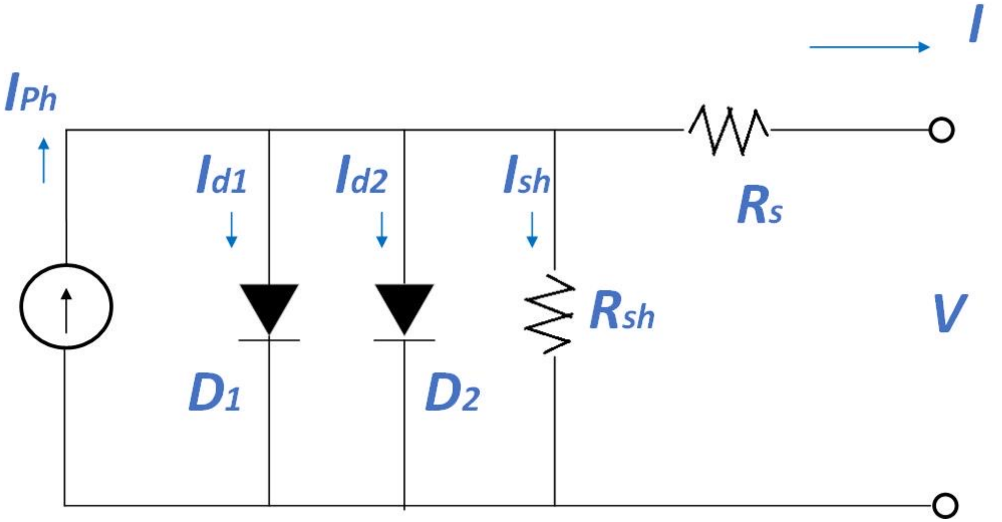

Figure 4-10: The two diode equivalent circuit.

$$I = I_{Ph} - I_{S1}\left[exp\left(\frac{V + I * R_S}{V_T}\right) - 1\right] - I_{S2}\left[exp\left(\frac{V + I * R_S}{2 * V_T}\right) - 1\right] - \frac{V + I * R_S}{R_{sh}}$$

- I_{S1}, I_{S2}: saturation currents of the two diodes.

Power electronics

- Many components required for PV system operation: balance of system (BOS)
- Type of components depend on whether it's grid-connected or stand-alone system
- Components include: mounting structures, energy storage, DC-DC converters, inverters, charge controllers, MPP tracking, cables etc.
- Electronic components classified as power electronics

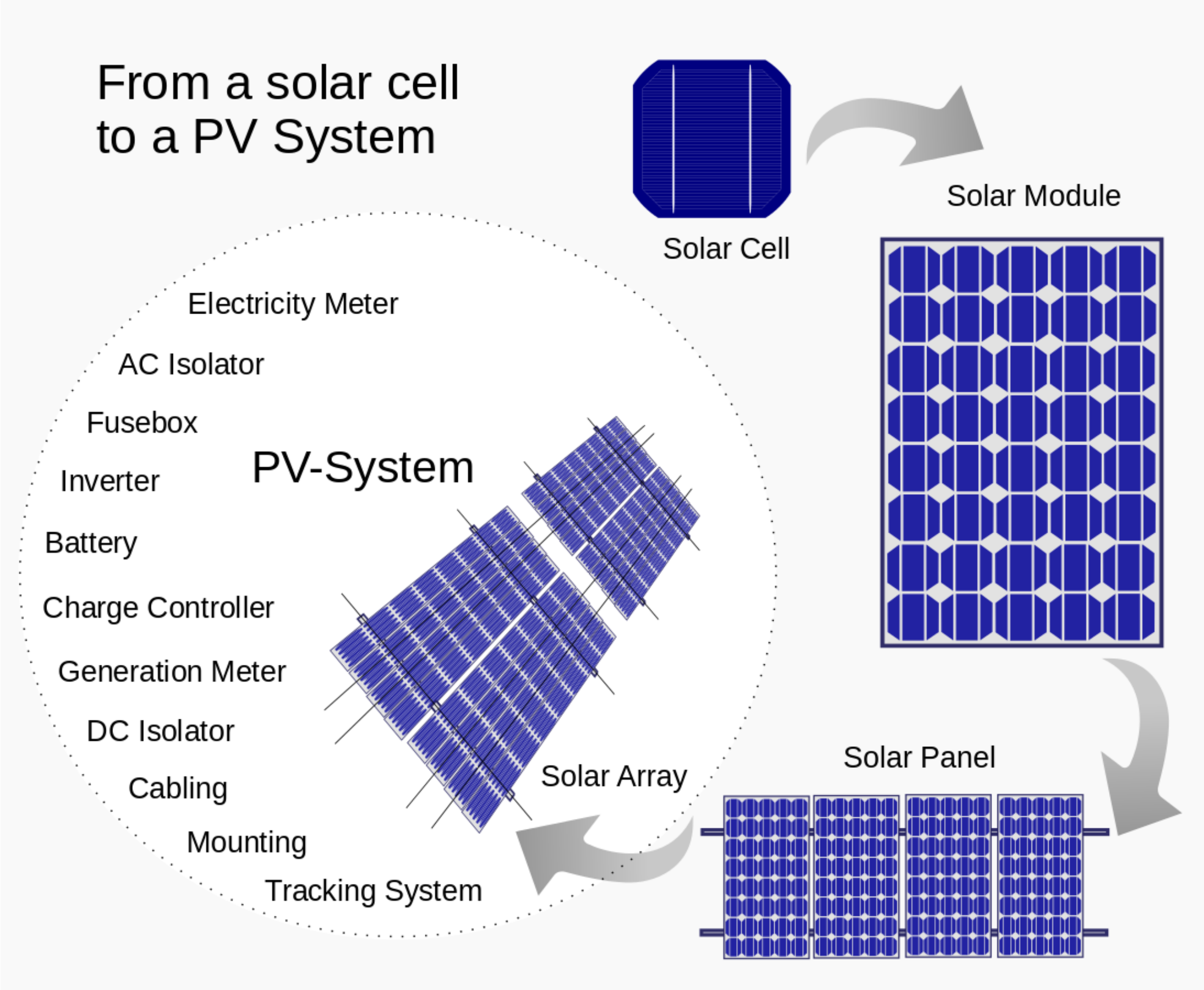

Figure 4-11: From solar cell to PV system.

Power electronics

DC-DC converter

- DC-DC converter used for multiple purposes
- Transforms variable voltage from solar panel to constant voltage, which will be used by DC-AC inverter
- Sets operating point of modules, which is controlled by MPP tracker
- In stand-alone systems, MPP voltage from module may not be the same with voltage required by batteries and electric load

Power electronics

DC-DC converter

- A simple load will have ohmic resistance R and will be represented by a linear load line in the module I-V curve, where I=V/R
- Intercept of load line with I-V curve gives load operating point
- Temperature, irradiance vary, I-V curve changes and operating point moves along load line. Not always near module MPP
- When far away from MPP, the PV module will contribute only a part of available power to load
- DC-DC converter used

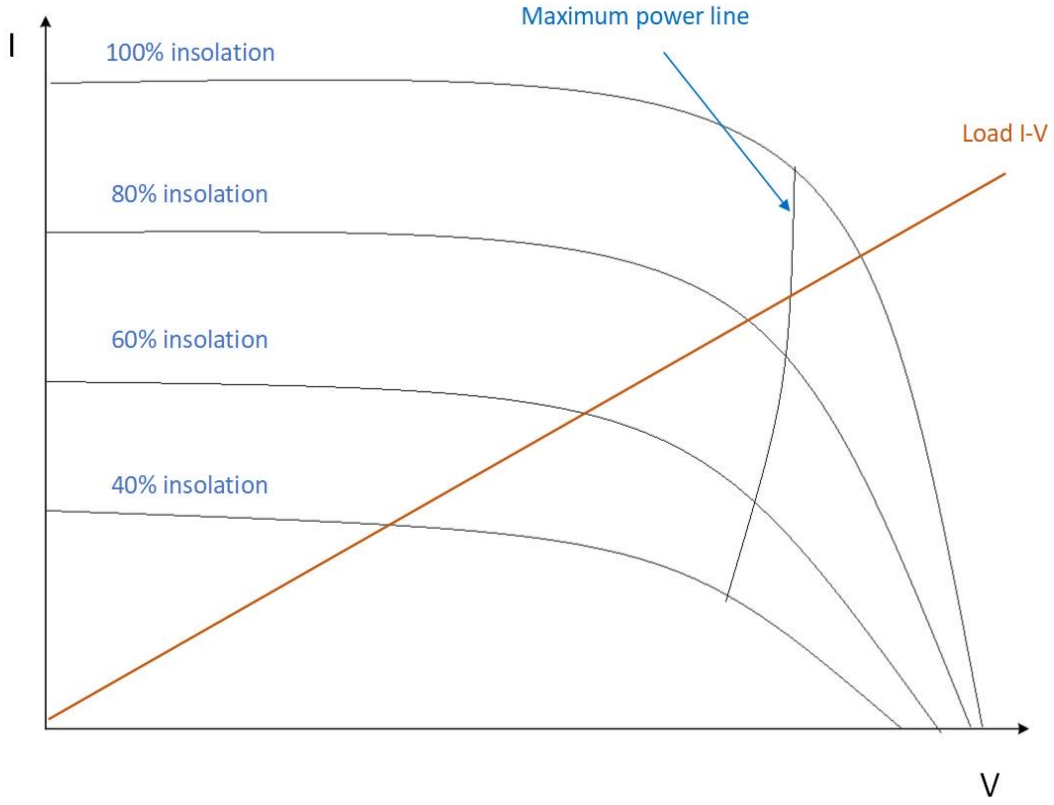

Figure 4-12: Load line with various I-V curves for different insolation levels.

Power electronics

DC-DC converter

- DC-DC converter is used to convert an input voltage of V_1 to an output voltage of V_2
- PV voltage can be selected independently of load voltage
- Ideal converter has 100% efficiency, output power=input power

$$P_1 = I_1 * V_1 = I_2 * V_2 = P_2$$

- In reality there's always some loss, converted to heat
- DC-DC converter can be buck converter, boost converter or buck-boost converter

Power electronics

DC-DC converter

- Buck converter used for voltage reduction
- Switch through input V_d for time period T_{on} to output V_0 (pulse width modulation, PWM)
- Switch is on: input voltage is applied to load
- Switch is off: load voltage is zero
- Pulsed voltage at output: $V_0 = \frac{T_{on}}{T} * V_d = D * V_d$
- T: total time period, D: duty cycle
- Pulsed voltage not acceptable. Inductor L added to maintain continuous current, capacitor C to smooth output voltage

Buck converter

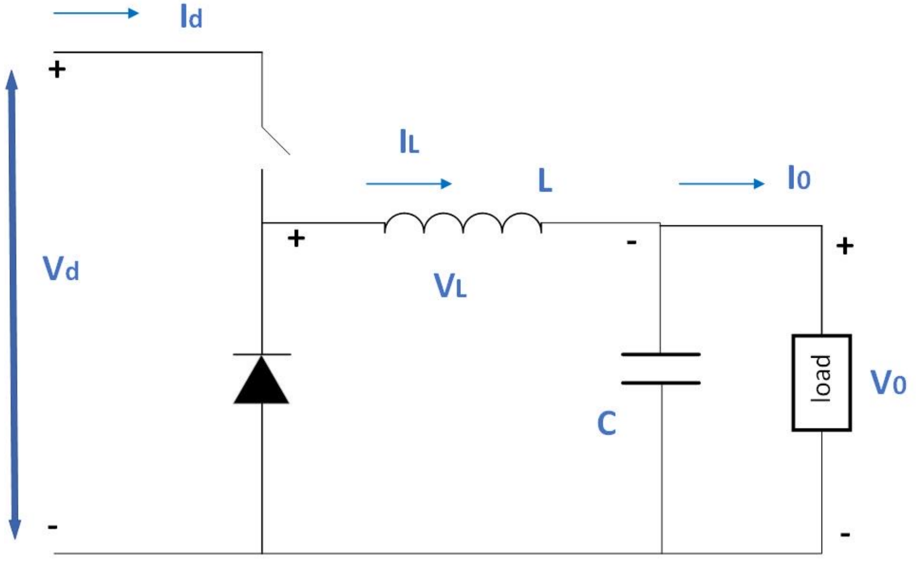

Figure 4-13: Buck converter circuit.

- In continuous mode operation, time integral of voltage across inductor during one switching cycle is zero.
- $V_0 \leq V_d$

Power electronics

DC-DC converter

Boost converter

- Boost converter used to convert small to higher voltage
- Time integral of voltage across inductor during one switching cycle is zero, for operation to be in continuous mode

$$V_0 = \frac{1}{1-D} * V_d$$

- When switch is on, energy is stored in inductor and later released against higher voltage V_0
- Energy is transferred from lower PV module voltage to higher load voltage

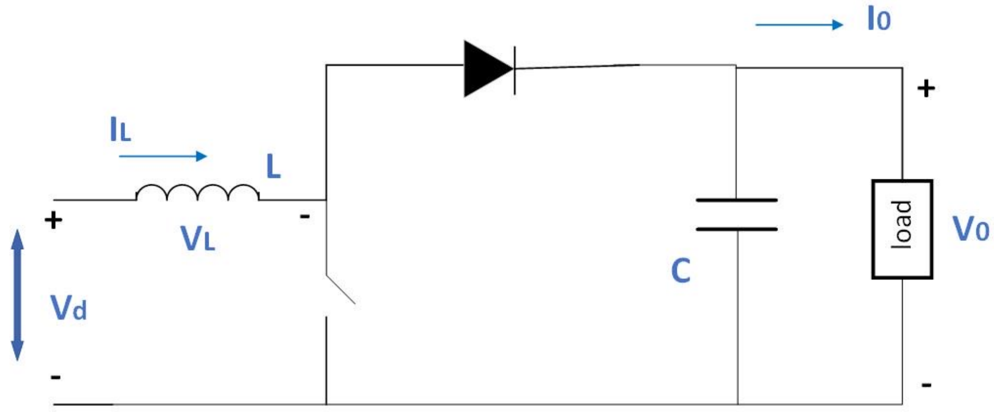

Figure 4-14: Boost converter circuit.

Power electronics

DC-DC converter

Buck-boost converter

- In a buck-boost converter, output voltage can be higher or lower than input voltage
- For continuous mode operation, time integral of voltage across inductor for the switching cycle must be zero
- Output voltage is then equal to: $$V_0 = \frac{D}{1-D} * V_d$$

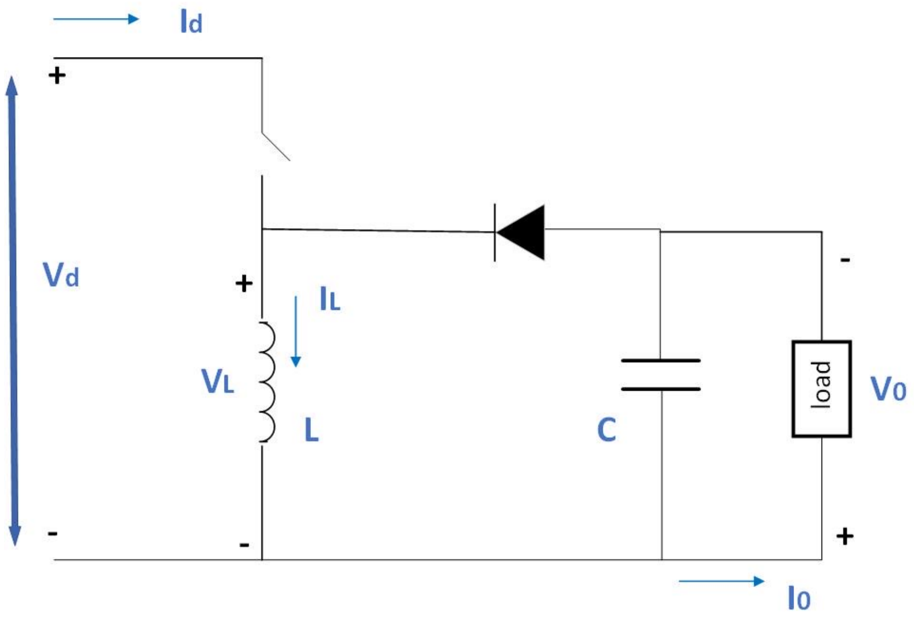

Figure 4-15: Buck-boost converter circuit.

Power electronics

Maximum power point tracking

- DC-DC converter used for MPP tracking
- Power at input or output of DC-DC converter can be found by measuring I, V
- By varying duty factor D, the operating point is varied
- Perturb and Observe method: MPP tracker starts at open circuit point in I-V curve. Actual power is determined and then D is increased. Tracking is correct if power now greater than before. D increased again.
- If MPP is exceeded then measured power is decreased. D is decreased.

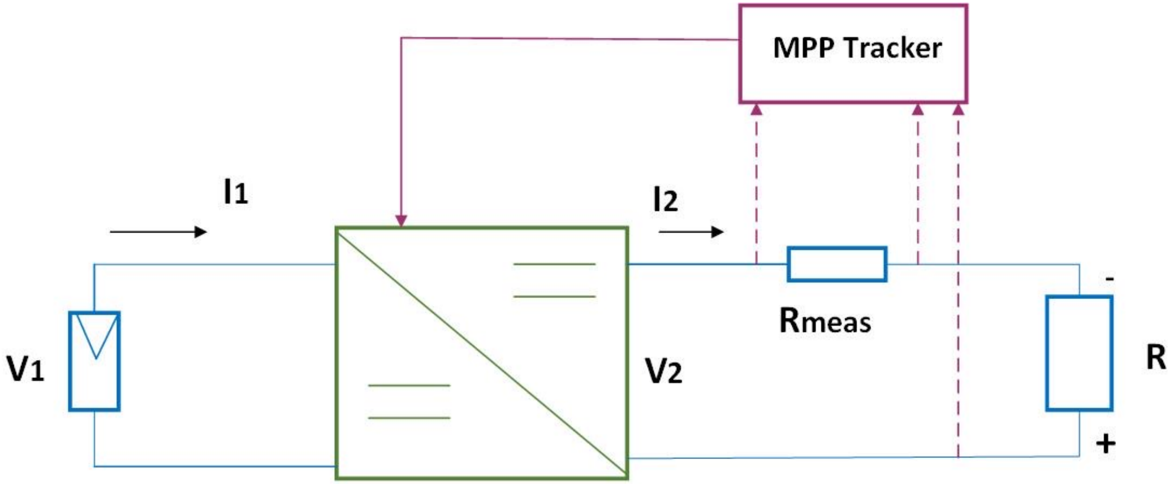

Figure 4-16: Circuit with DC-DC converter and MPP tracker.

- Operating point varies a little around MPP

Power electronics

Inverters

- An inverter converts DC to AC current, for PV systems that power AC loads (e.g. grid-connected systems)
- AC from inverter must be in sinusoidal form, synchronized to grid frequency
- Feed-in voltage mustn’t exceed grid voltage. Inverter must disconnect if grid voltage is turned off
- Central inverter: PV modules connected in strings, strings in parallel connected to a central inverter, which feeds power to the grid
- Need for only one inverter
- Non uniform shading will lead to mismatching losses, long DC wires, no flexibility

Power electronics

Inverters

- ○ String inverter: each string connected to a separate inverter, own MPP tracker
- ○ Simpler cabling but still unequal current within string
- ○ Micro inverter: each module connected to own inverter, can operate at its MPP
- ○ Inverter attached directly to module, subject to weather conditions
- ○ Highest cost of inverters architecture

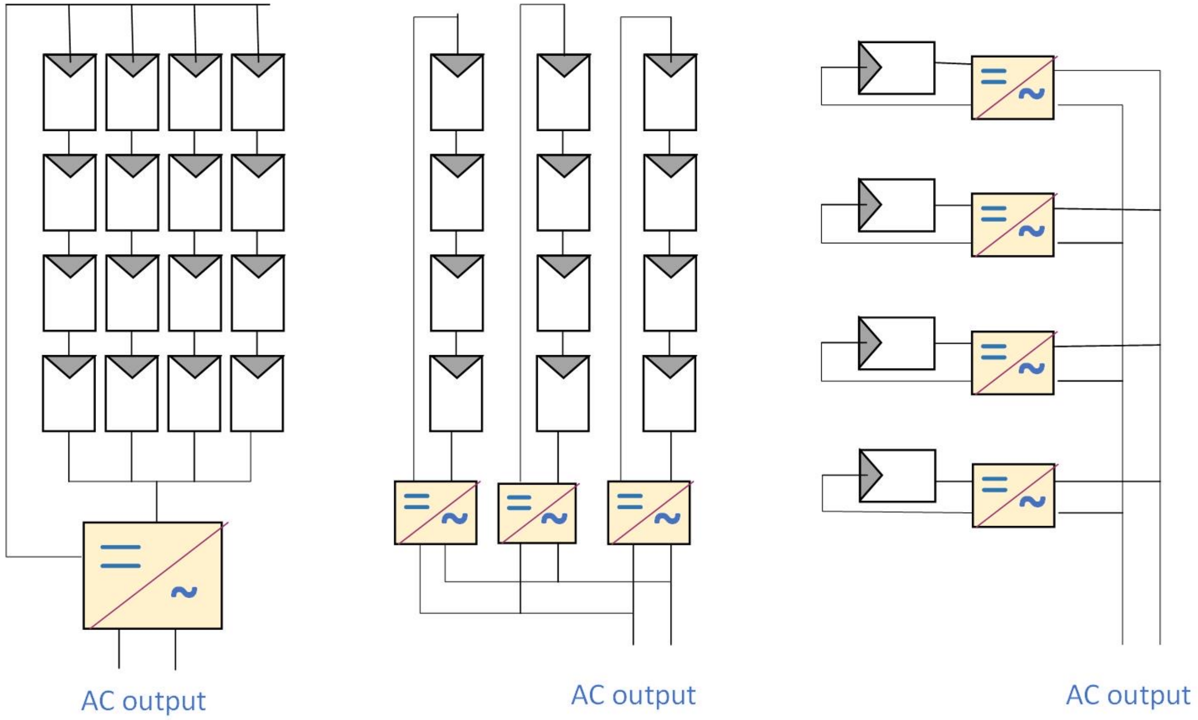

Figure 4-17: Inverter topologies: central inverter (left), string inverter (middle), micro inverter (right).

Power electronics

Inverters

- Inverter with optimizers: hybrid of central and micro inverters
- Optimizer box connected to each module, containing MPP tracker and DC-DC converter
- Optimizer boxes connected in series and are all connected to central inverter
- Each module operates at its MPP, all optimizers operate at voltages near the module voltage, DC-DC conversion very efficient

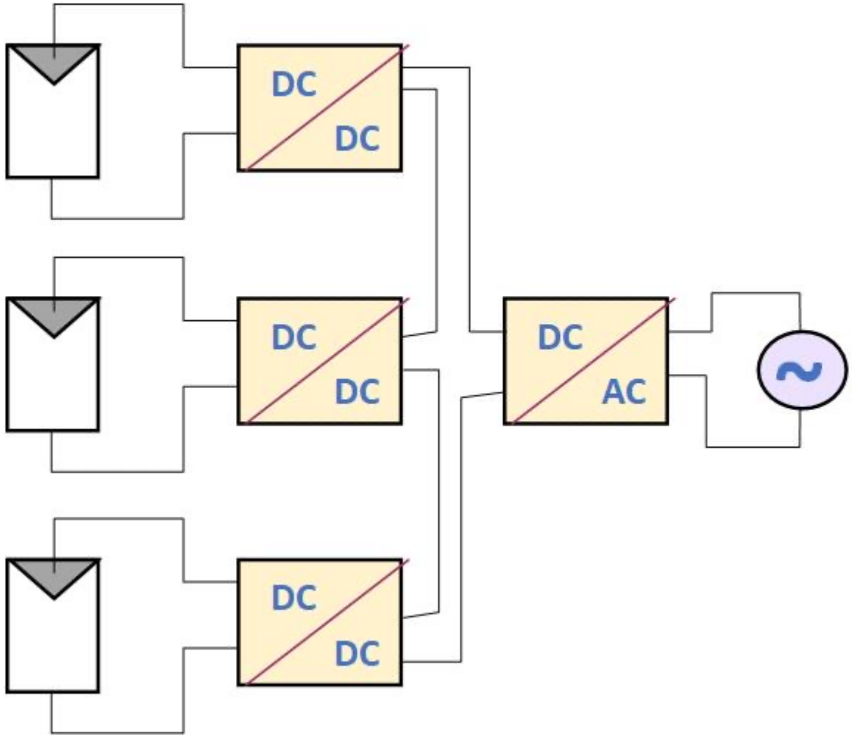

Figure 4-18: Inverter with optimizers.

Power electronics

Inverters

H-bridge inverter

- H-bridge (full bridge) inverter: DC input connected to load (AC output), placed between 4 switches
  - All switches open: no current across load
  - S1, S4 closed: current across load from left to right (+ to load left side, - to load right side)
  - S2, S3 closed: current across load from right to left (- to load left side, + to load right side)
- Voltage across load can be $+V_S$, 0, $-V_S$
- AC current switches between positive and negative voltages
- Inverter switches between 2nd and 3rd mode continuously, providing square wave

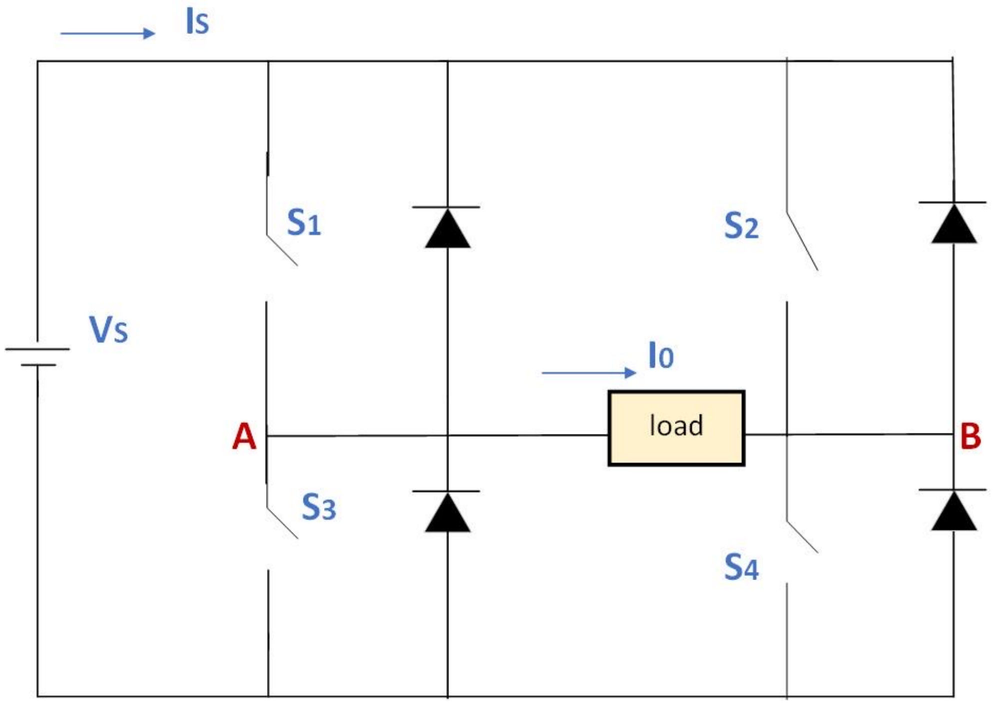

Figure 4-19: H-Bridge inverter diagram.

Power electronics

Inverters

H-bridge inverter

- Square wave not suitable for some applications
- Pulse width modulation (PWM): 2nd and 3rd mode have role of a buck converter
- Circuit with low pass filter of inductors and capacitors: high frequency components filtered, produced wave will be smooth sine curve
- Diodes in parallel: if switch goes from “on” to “off” fast, current will still flow, no high induced voltages

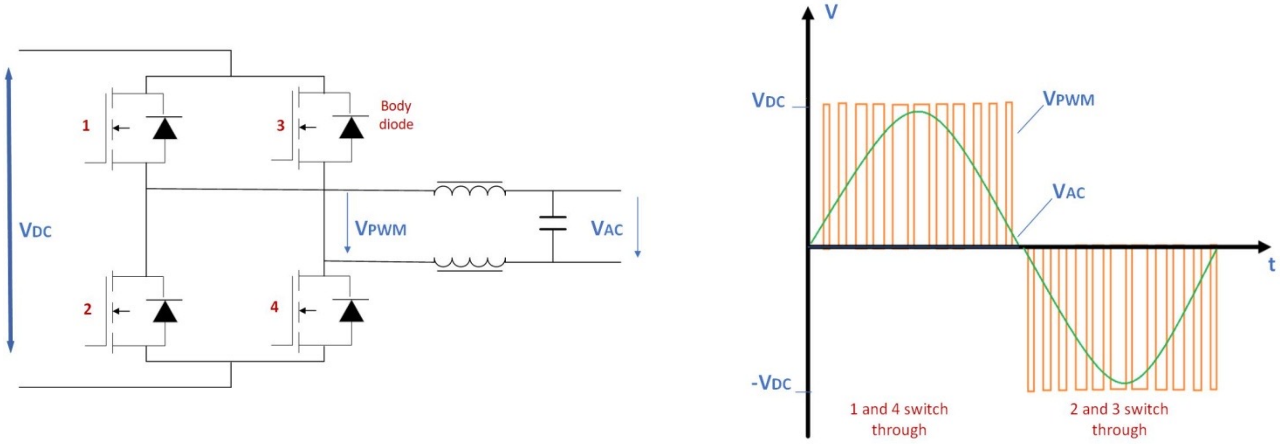

Figure 4-20: H-bridge with low pass filter (left) and output sine signal (right).

Power electronics

Inverters

H-bridge inverter

- If PV voltage is low, boost converter is used to increase it before going to inverter or transformer is used to transform low AC to desired AC voltage
- Circuit without transformer: DC voltage after boost converter is converter by PMW bridge into sinusoidal voltage which can be fed into grid
- No transformer, no galvanic isolation. A residual current protective device used to protect from sudden current changes
- Grid monitoring ensures voltage and frequency are within range for grid feed-in

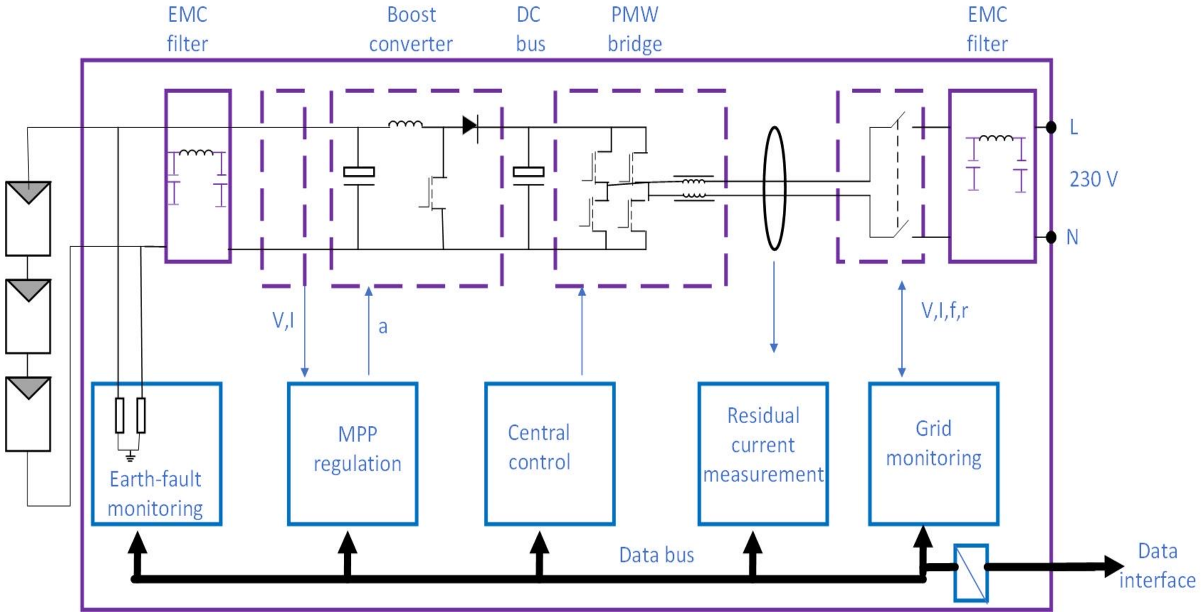

Figure 4-21: Inverter arrangement without transformer.

Power electronics

Inverters

Three-phase inverter

- Higher power inverters needed for large installations
- Inverters to feed three-phase power to the grid
- Three-phase inverter similar to single phase inverter, but consists of three legs
- Each leg creates a sinewave output with a phase shift of 120° between them

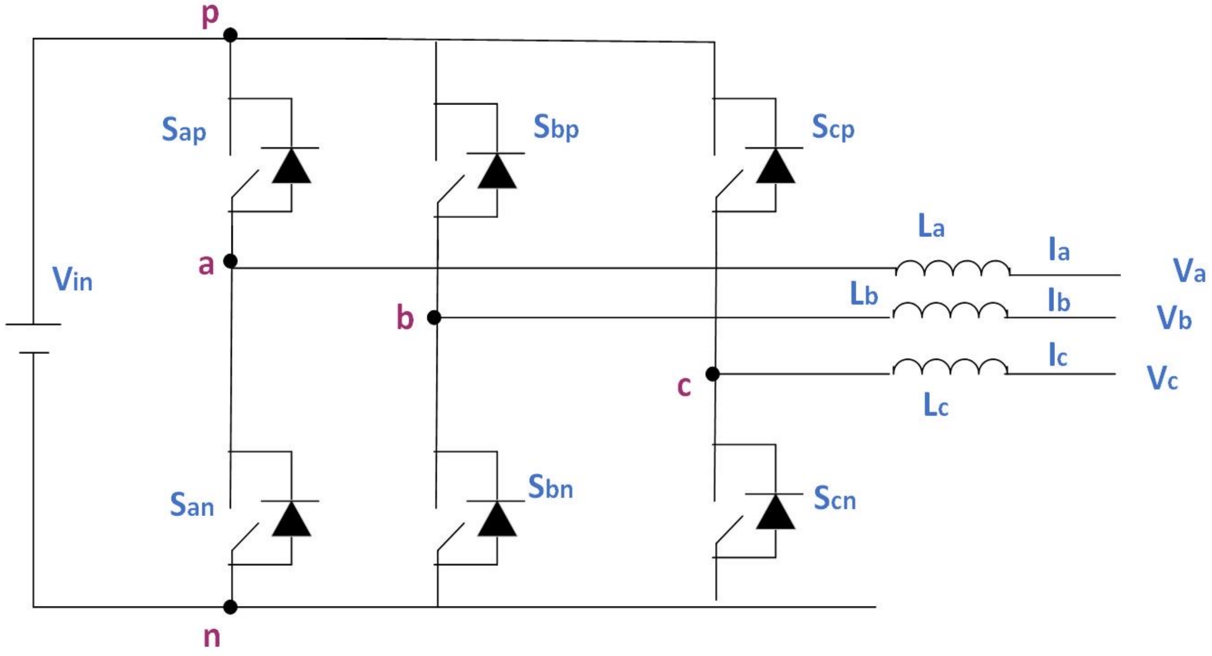

Figure 4-22: Three-phase inverter.

Power electronics

Inverters

Half-bridge inverter

- Half-bridge inverter: two switches, other two switches replaced with capacitors
- Midpoint between two capacitors is grounded
- Simpler configuration
- High DC voltage required
- Peak output voltage is half of DC supply voltage. In H-bridge inverter, it's the same

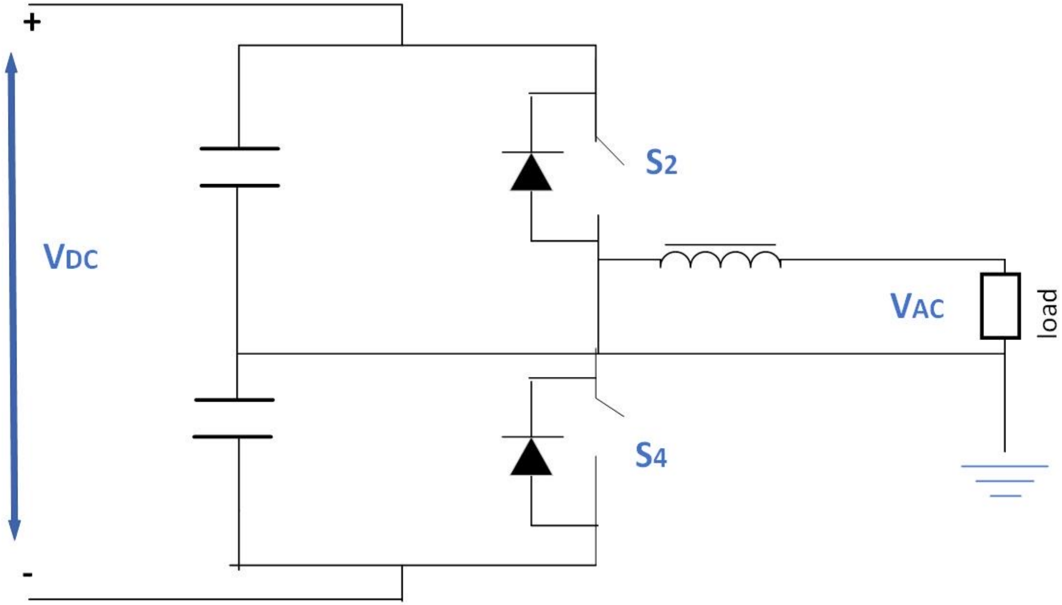

Figure 4-23: Half-bridge inverter.

Power electronics

Power converter efficiency

- Efficiency of DC-DC or DC-AC converter: $\eta = \frac{P_0}{P_0 + P_d}$ P_0: output power, P_d: dissipated power
- Dissipated power represents power lost at various electric circuit components

$$P_d = P_L + P_{switch} + P_{other}$$

P_L: loss in inductor, P_{switch}: loss in switch, P_{other}: other losses in circuit

- Complete inverter unit: efficiency is ratio of output AC power to input DC power

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}}$$

- Maximum efficiency depends on applied input voltage

Power electronics

Batteries

- Batteries are essential for energy storage, especially in stand-alone systems
- Types: lead-acid, nickel-metal hydride, nickel-cadmium, lithium-ion, lithium-polymer
- Lead-acid most popular, lowest cost
- Nickel-metal hydride (NiMH) have high energy density but high rate of discharge
- Nickel-cadmium (NiCd) have lower energy density but cadmium is toxic
- Lithium-ion (Li-ion) and lithium-ion polymer (LiPo) have high energy density but high costs. Technology new compared to lead-acid

Power electronics

Batteries

- Redox flow: combination of batteries and fuel cells
- Positive and negative liquid electrolytes, separate by membrane
- Only protons can pass through the membrane
- Charging, discharging can happen without mixing of reactants, which prevents liquids from ageing
- Increase tanks size, stored chemical energy can be increased
- Increase membrane area, maximum output power can be increased
- Complex structure (pumps etc.)

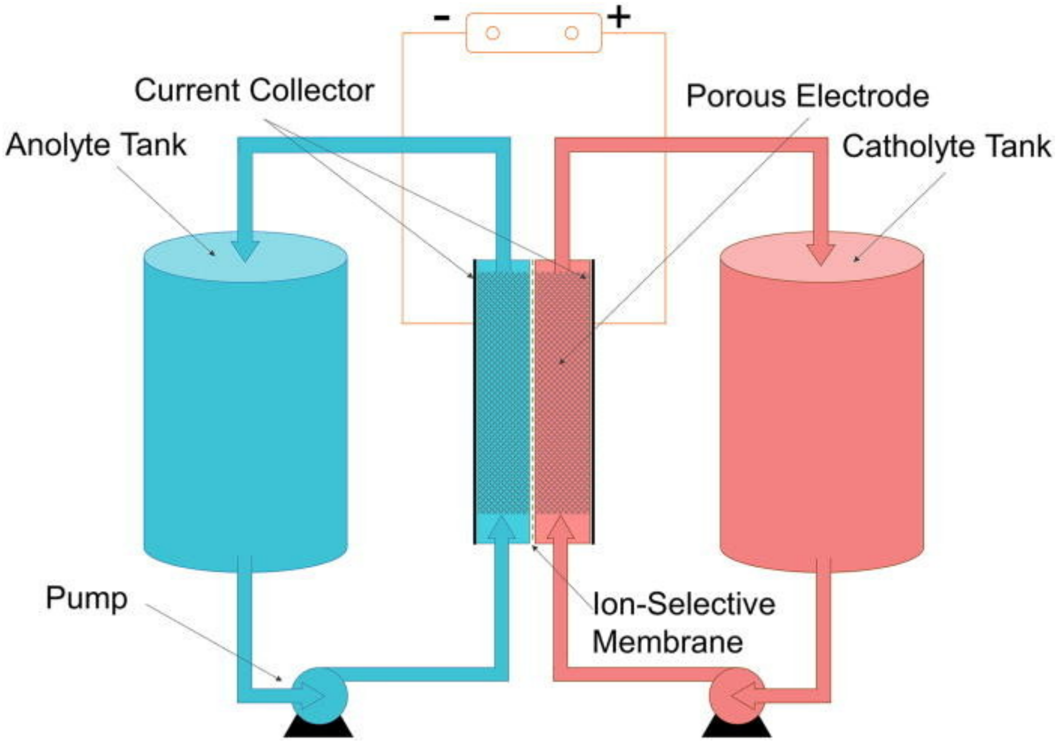

Figure 4-24: Diagram of a redox flow battery.

Power electronics

Batteries

- Lead-acid: diluted H_2SO_4 as electrolyte, Pb and PbO_2 are the constituents of negative and positive electrode
- Discharging: electrons flow from negative to positive electrode via external circuit, causing chemical reaction between plates and electrolyte
- Charging when higher voltage source is connected, flow of electrons reversed
- Energy stored in electrolyte, density increases during charging

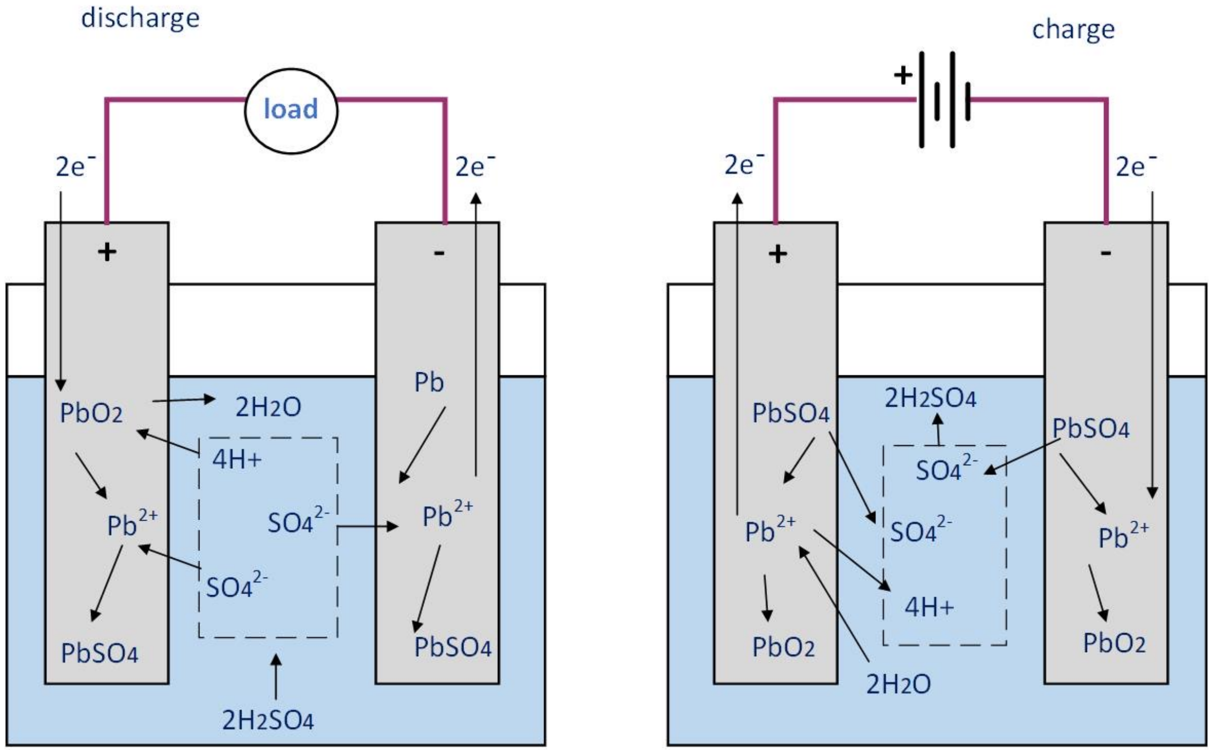

Figure 4-25: Lead-acid battery discharge and charge cycle.

- Voltage source is PV module
- In grid-connected systems, batteries can be charged by inverter

Power electronics

Batteries

Battery parameters

- Lead-acid batteries in PV have nominal voltages of 12, 24 or 48 V
- Battery capacity, C_{bat} (Ah): amount of charge delivered by battery at nominal voltage
- Energy capacity is product of nominal voltage and battery capacity
- Round-trip efficiency is ratio of total storage output to total storage input:
- Voltaic efficiency, η_V: ratio of average discharging voltage to average charging voltage
- Coulombic efficiency, η_C: ratio of total charge extracted from battery to total charge put in battery in a full charge cycle

$$\eta_{bat} = \frac{E_{out}}{E_{in}}$$

$$\eta_V = \frac{V_{discharge}}{V_{charge}}$$

$$\eta_C = \frac{Q_{discharge}}{Q_{charge}}$$

Power electronics

Batteries

Battery parameters

$$\eta_{bat} = \eta_V * \eta_C = \frac{V_{discharge}}{V_{charge}} * \frac{Q_{discharge}}{Q_{charge}}$$

- Battery state of charge (SoC): percentage of battery capacity available for discharge

$$SoC = \frac{E_{bat}}{C_{bat} * V}$$

- Depth of discharge (DoD): percentage of battery having being discharged.

$$DoD = \frac{C_{bat} * V - E_{bat}}{C_{bat} * V}$$

- Cycle lifetime is number of charging and discharging cycles before capacity drops below 80% of nominal value
- Lifetime increases in cold temperatures
- Capacity decreases with temperature decrease

Power electronics

Charge controllers

- Charge controller controls current that flows between battery, PV module, load
- Protects battery from overload and deep-discharge
- Prevents unwanted discharging
- Monitors state of charge
- May be used for voltage conversion and MPP tracking

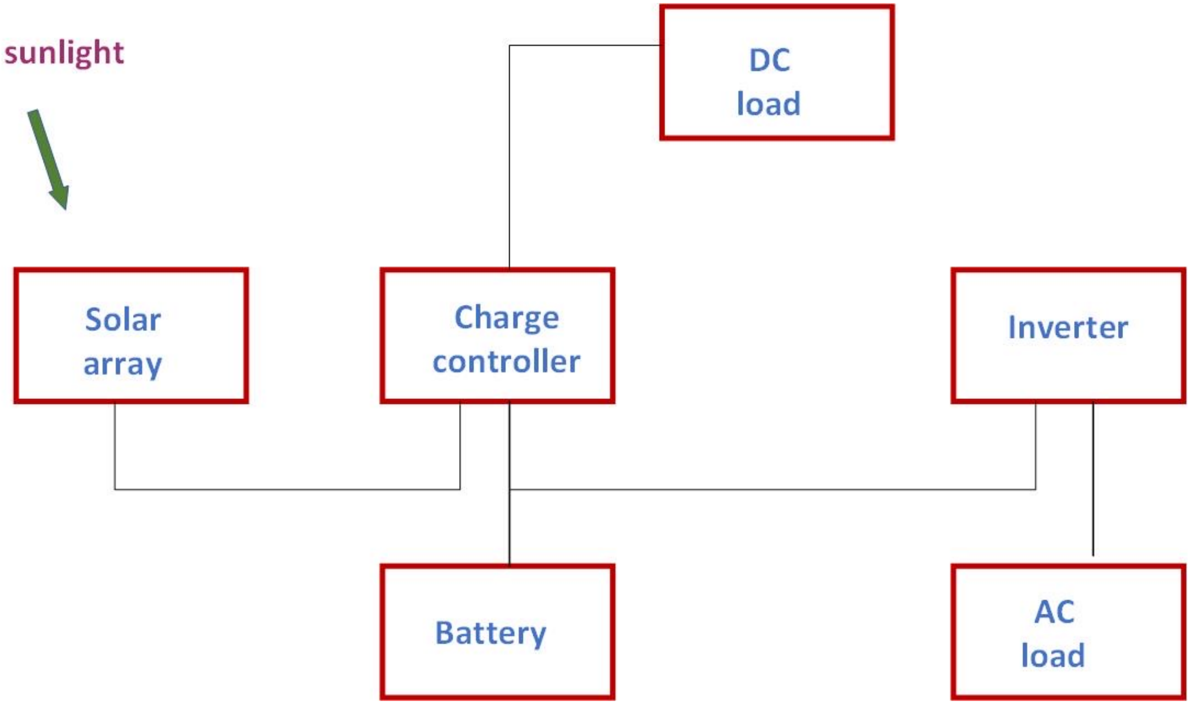

Figure 4-26: Position of charge controller in a PV system.

Power electronics

Charge controllers

- Series charge controller: prevents overcharging by disconnecting PV panel, turns switch 1 off
- Switch 2 is turned off to protect from deep-discharge
- Shunt charge controller: connected in parallel to PV panel
- Overcharging prevented by short-circuiting panel, no current to battery
- Switch 2 off to ensure deep-discharge protection

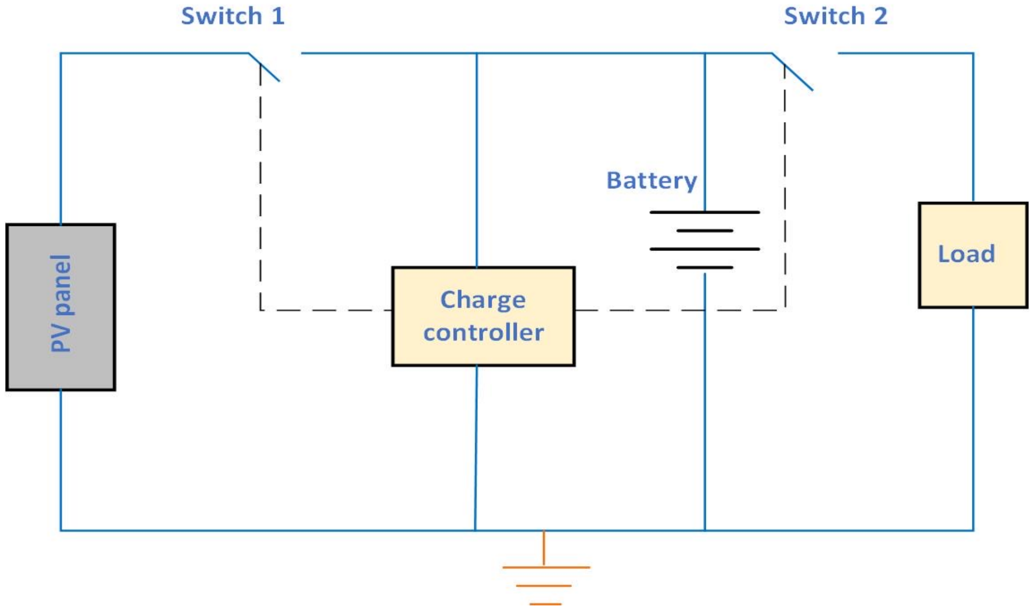

Figure 4-27: Series charge controller.

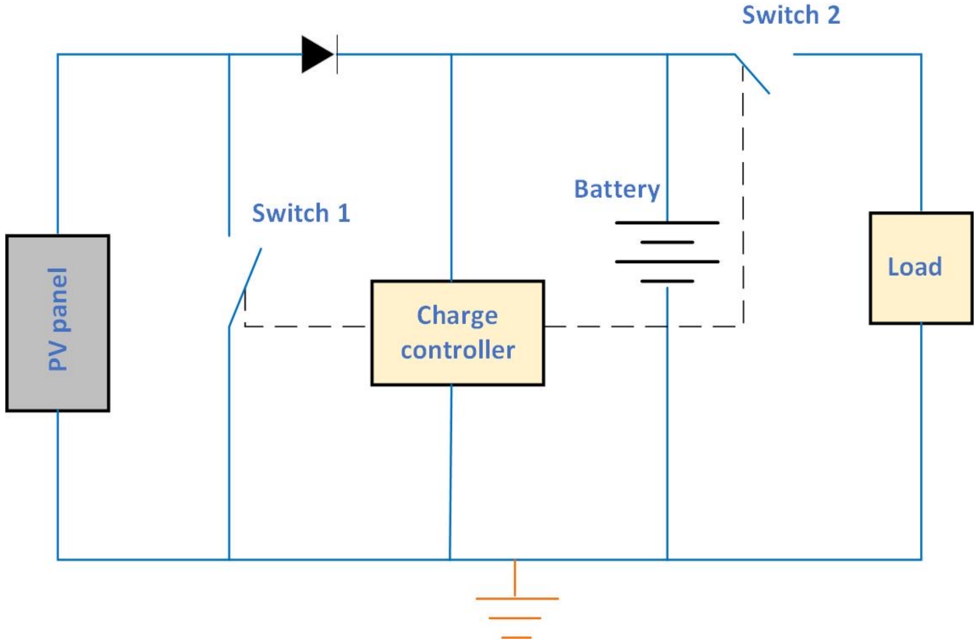

Figure 4-28: Shunt charge controller.

Design of PV system

Types of PV systems

- PV systems vary in size, from small (module plus load) to large power plants
- May provide power to both DC and AC loads
- May include reserve power, backup generator
- Stand-alone: independent of utility grid. May include batteries and charge controllers
- Grid-connected: connected to grid, include inverters, may include batteries. Excess energy transported to the grid, when more energy is needed it's taken from the grid
- Hybrid: combination of PV modules and other energy source, e.g. wind, gas or diesel generator. Include batteries, charge controllers
- Stand-alone and hybrid can include inverters if they are to power AC loads

Design of PV system

Stand-alone PV system

- Design of a PV system includes planning, assessment of load and solar resource, solar array requirements determination, arrangement of modules, selection of suitable components
- *Energy requirement assessment.* select system nominal voltage: 12, 24 or 48 V
- Daily energy (Wh) requirement of DC load: power rating of appliance (W) x average daily operational time (h)
- Ampere-hours (Ah) of appliance: Wh / nominal voltage

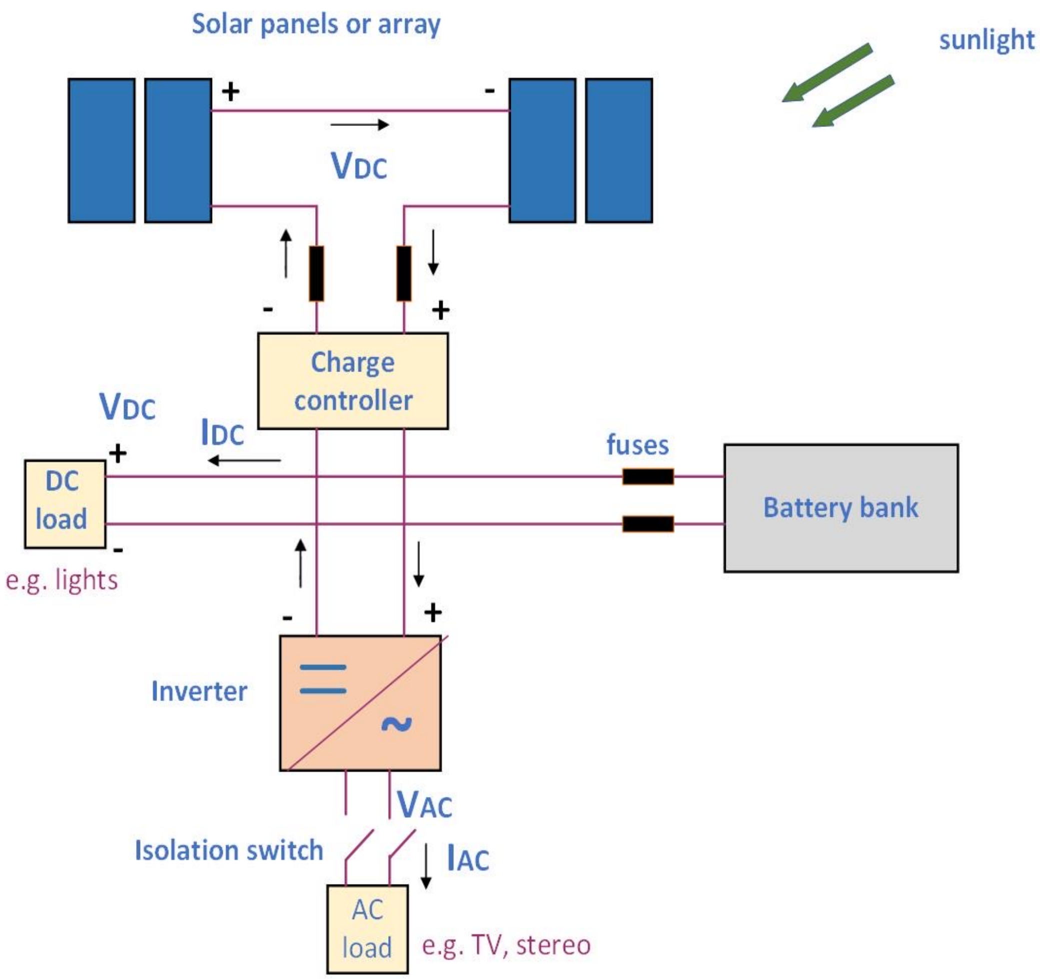

Figure 4-29: Simple design of a stand-alone PV system.

Design of PV system

Stand-alone PV system

- AC loads: AC load energy use divided with inverter efficiency. Then division with nominal system voltage to determine Ah
- Loads energy requirements must be increased by 20-30% to account for energy losses in batteries, charge controllers etc.
- *Solar resource assessment.* Spectrum for Air Mass=1.5 usually used, normalized has total irradiance 1000 W/m^2 = 1 equivalent sun hour (ESH)
- If annual solar irradiation is 1000 kWh/m^2 on horizontal plane, then 1000 ESH / 365 days gives 2.7 average daily sun hours.
- If module in tilted position, this is higher
- Average value of 3 ESH is assumed

Design of PV system

Stand-alone PV system

- *Solar array requirements.* Total current that solar array must generate is calculated by dividing DC energy requirement (Ah), including losses, with daily ESH (e.g. 3 ESH)
- Determine solar array arrangement, figure minimum number of modules to produce calculated energy requirement
- Modules in series: nominal voltage increased. To determine their number, the nominal PV voltage is divided with voltage at maximum power
- Modules in parallel: higher current. To determine their number, total required current is divided with produced current of each module at maximum power
- Total number = number in series x number in parallel
- Output modules voltage should fit battery voltage and be within range of inverter MPPT

Design of PV system

Stand-alone PV system

- *Battery requirements.* Determine battery size to have desirable reserve time
- Battery reserve capacity is used at night or cloudy conditions
- Capacity will provide required energy for a number of days, the “days of autonomy”
- Days of autonomy differ depending on load
- Residential systems around 5 days. Essential loads around 10 days or more
- Battery capacity (Ah) = daily DC energy requirement (with losses) x number of days of reserve time that is recommended

Design of PV system

Stand-alone PV system

- *Load profiling.* Determine maximum load and average daytime and night time energy requirement
- Load may need constant power for specific time or be turned on-off
- Different loads may draw power at the same time or different times, have different time variations in their usage
- Total energy consumed calculated for whole year (kWh/year)

$$E_L^Y = \int_{year} P_L(t)dt$$

$P_L(t)$ is load power at time t

Design of PV system

Stand-alone PV system

- *Charge controller selection.* Protection from battery overcharge and deep-discharge
- Each battery has different charging routine, change controller must be selected for specific battery of PV system
- Typical charge controller efficiency: 85-95%
- *Inverter selection.* Inverter when AC power is required
- Should have same nominal input voltage as battery voltage and be large enough to handle total amount of power used at one time
- Inverter should be 20-30% larger than total power of appliances, able to supply continuous AC power, provide sufficient surge capability
- Typical inverter efficiency: 80-90%, good inverter up to 95%

Design of PV system

Stand-alone PV system

- *Mounting and tracking.* Mounting system can be ground mount, roof mount or pole mount
- Tracking system to increase received power: 20-25% for single axis tracking, 30% for double axis tracking
- *Wiring selection.* Wire should be large enough to carry maximum current without important voltage losses
- Wire resistance causes voltage drop from source to load so minimum wire length is best
- Wire specifications based on calculated output current and system voltage
- Decide number and type of switches, circuit breakers, fuses etc.
- *Shading analysis.*

Design of PV system

Grid-connected PV system

- Grid-connected systems use PV generated energy in the day and grid power at night
- Excess generated power is fed into utility grid or stored in batteries if available
- System connected to grid on permanent basis, so solar energy consumption, panel size calculations are not necessary
- When excess power is fed to grid, electric meter is rotated backwards (net metering)
- Billing is done based on net amount of electricity
- Electrical meter measures energy leaving and entering the system to calculate net energy consumption

Design of PV system

Grid-connected PV system

- ○ Choice of inverter based on maximum high and low voltage power it can handle and efficiency
- ○ Electric meter (kWh): twin meters, one measures energy consumption other energy fed into grid or bidirectional meter, measuring net electricity received from grid
- ○ AC breaker panel or fuse box
- ○ Extra breakers for inverter and filter connections
- ○ Isolator, safety switches

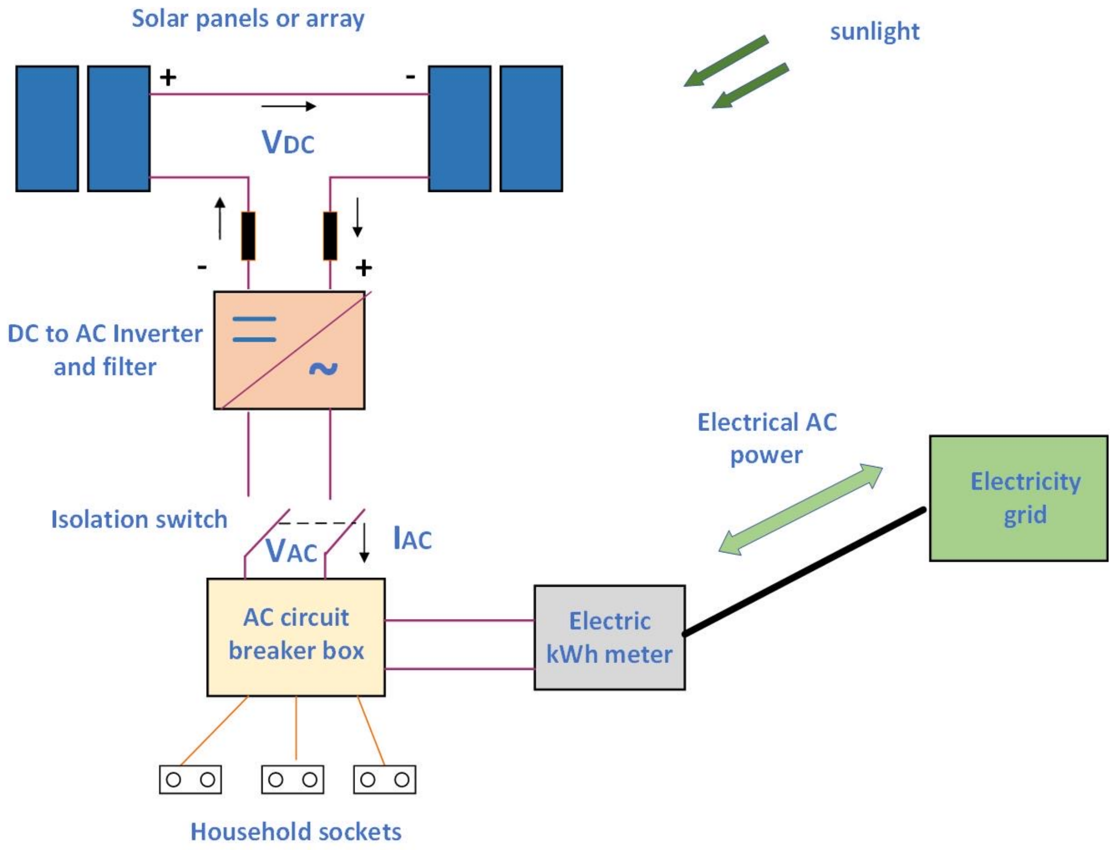

Figure 4-30: Simple design of a grid-connected PV system without batteries.

Design of PV system

Grid-connected PV system

- Grid-connected system may have batteries to be independent
- Energy can be drawn from batteries instead of grid
- Batteries for short term storage (few hours or days) or long term storage (few weeks)
- Batteries and charge controllers increase cost

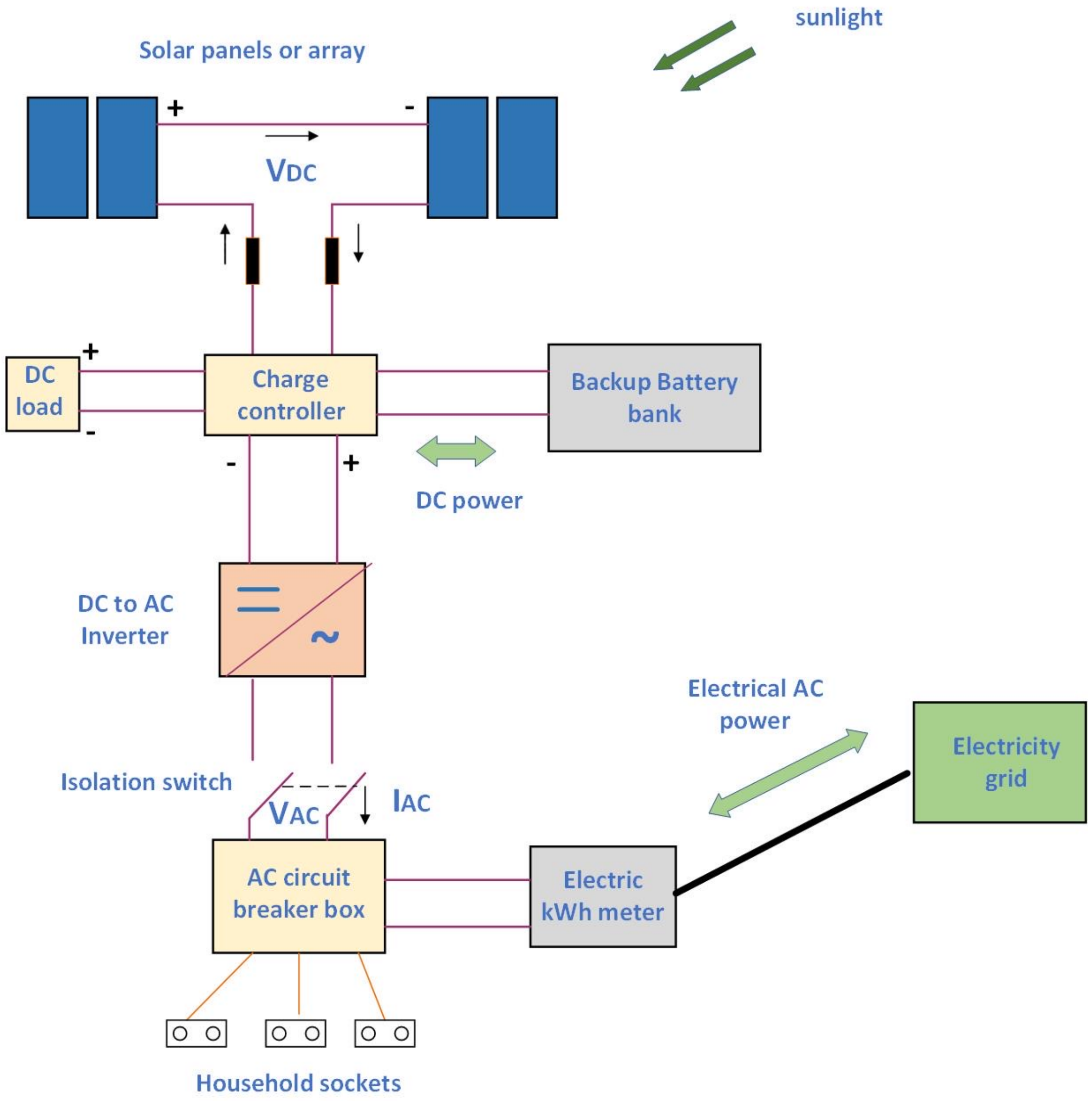

Figure 4-31: Simple design of a grid-connected PV system with batteries.

Design of PV system

Hybrid PV system

- PV modules plus another energy source, e.g. wind turbine, diesel generator
- May include storage and connected to AC network
- Multifunctional inverter to convert DC to AC current, control power generation, storage, voltage, frequency
- PV-diesel: generator should be used for loads at 80% of its rated capacity, not small loads
- Generator consumes more energy at its start, should run for specified minimum time

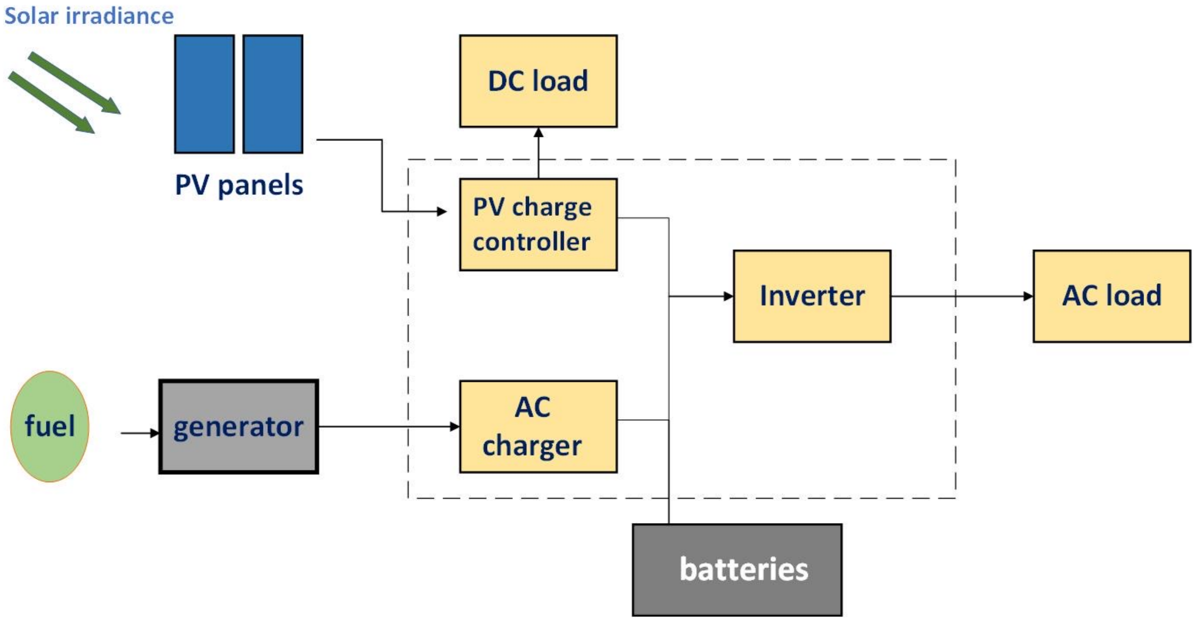

Figure 4-32: Design of a hybrid PV-diesel system.

Design of PV system

Hybrid PV system

- Excess energy from PV and generator, stored in batteries
- Loads may be DC and AC, inverter required and AC charger to transform AC from generator into DC to charge batteries
- Bi-directional inverter combines inverter and AC charger
- Devices chosen so PV and generator can charge battery and rated charging current match maximum charge current of battery

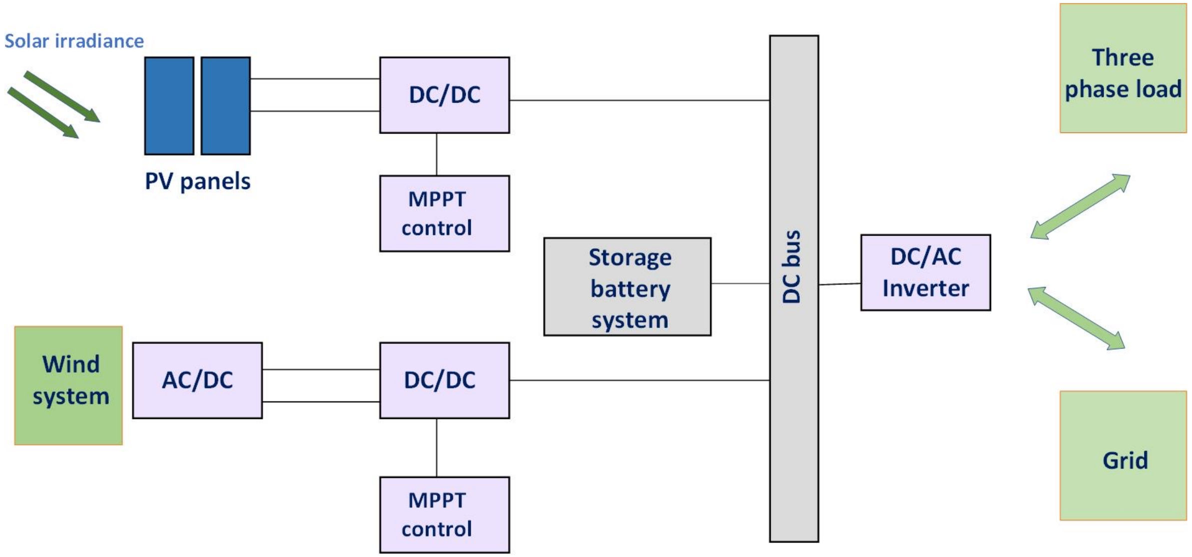

Figure 4-33: Design of a hybrid PV-wind system.

Design of PV system

Hybrid PV system

- To choose system, assessment of PV module is required
- Hybrid system should deem preferable to pure diesel generator
- Load forecast essential in hybrid design
- Average daily total energy requirement, average daily peak power and its time, maximum peak power in high season, average and maximum demand levels in the time period that PV modules operate, amount of energy used during the night, need to be determined
- Advantage of ability to supply low load for large time during night, using battery storage, generator used to cover evening peak and contribute to battery charge

Design of PV system

PV simulation tools

- PV system is designed with help from software tools
- *Dimensioning tools:* calculate PV system dimensions in regards to input data, e.g. load data, climate data, system components
- Determine optimal size of components, given desired energy output
- Dimensioning with focus on life-cycle cost of system or system function

Design of PV system

PV simulation tools

- *Simulation tools:* simulate PV system behaviour in given time period, based on input data
- User must specify type, size of system components
- Time resolution depends on input data resolution, like weather data
- Hourly resolution is common, provides system performance under various conditions, impact of changes in components operation etc.
- Life-cycle cost and emissions information can also be provided
- Some simulation tools provide system dimensioning also

Design of PV system

PV simulation tools

- *Research tools:* simulate different systems for research purposes
- Allow flexibility in modifying algorithms, to study behaviour and interactions of various system components
- *Mini-grid design tools:* help in design mini-grid electrical distribution network
- Help choose suitable system (e.g. stand-alone) to power house in village
- Help minimize power losses with correct voltage and wiring selection

Design of PV system

PV simulation tools

- RETScreen: focus on preliminary study and general dimensioning
- HOMER: allows comparison between DC and AC coupled systems, focus on economic aspects
- PV-SPS, PV*SOL, Pvsyst: provide detailed configuration
- Hybrid2, PV-DesignPro: system analysis
- TRNSYS, MATLAB/Simulink: detailed research focus
- Results of software tools depend on input data quality and rely on user knowledge and experience

- In this chapter, the photovoltaic circuit was presented. The power electronics of a PV system were described and the design of the various types of photovoltaic systems was given.

Summary

Photovoltaic system components

Thank You

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

Dr. Efterpi Nikitidou

Dr. Andreas Kazantzidis

Introduction to Renewable Energy

Lecture 5: Photovoltaic system calculation and aspects

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Introducing Recent Electrical Engineering
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Introduction to Renewable Energy

Lecture 6: Solar thermal systems

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

Section Outline

In this section, solar thermal systems are discussed, describing the technologies of concentrated solar power and thermal energy storage. Solar water heating systems are presented and various issues of a CSP system are described.

Section 1

Solar thermal systems

This week's topics…

- Concentrated solar power technologies
- Thermal energy storage
- Solar water heating
- CSP system
- Hybridization

CSP technologies

- Concentrated solar power (CSP) technologies use mirrors or lenses to concentrate sunlight to a receiver
- Sunlight is converted to heat to drive a heat engine connected to a power generator to produce electricity
- Direct solar irradiance is utilized
- CSP systems operate best in arid, semi-arid areas
- Heat engine is usually a steam turbine (Rankine cycle)

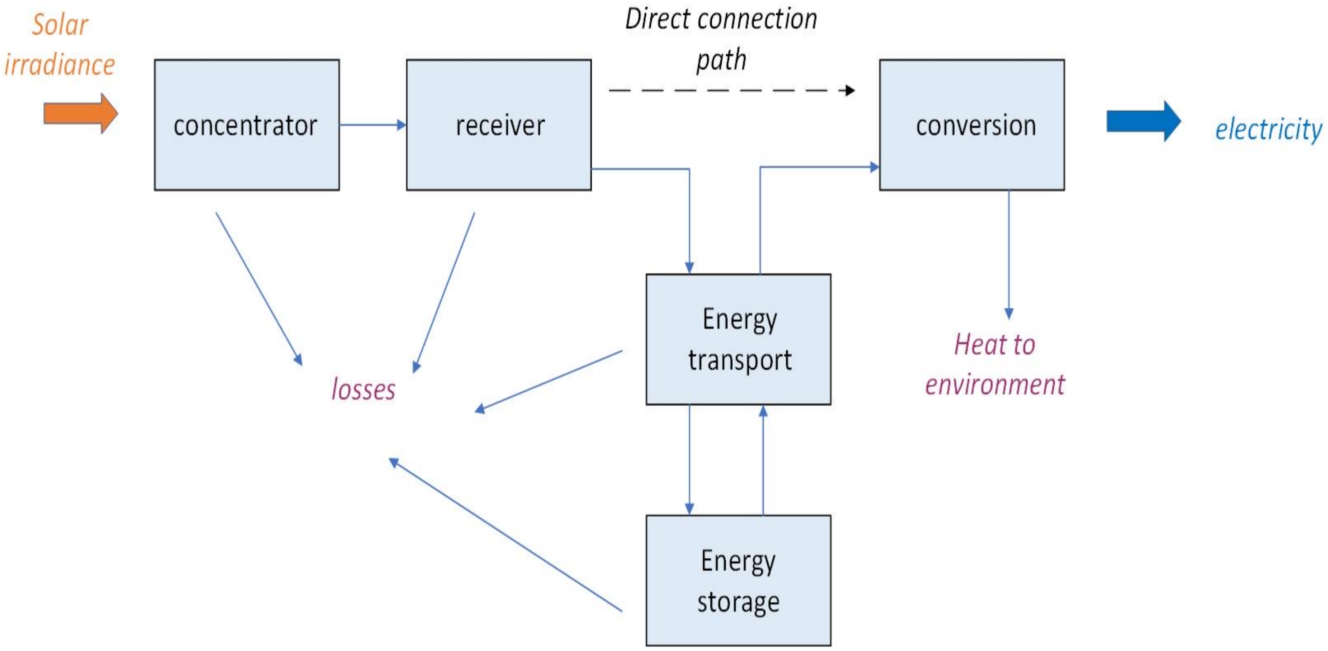


Figure 6-1: Basic process in a solar thermal power system.

CSP technologies

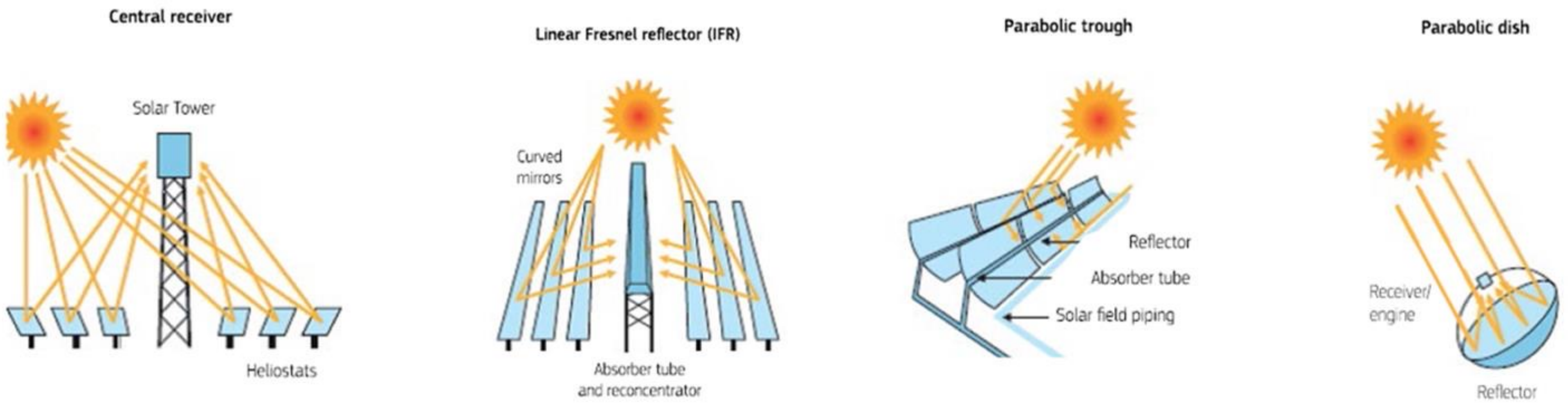


Figure 6-2: Concentrating solar power types: central receiver (solar power tower), linear Fresnel reflector, parabolic trough concentrator and parabolic dish concentrator.

- CSP technologies: parabolic trough, solar tower, linear Fresnel reflector, parabolic dish concentrator
- Linear-focusing systems can concentrate radiation by 50-100 times
- Point-focus systems concentrate radiation by 500-several thousand times
- Collector efficiency decreases with temperature while heat engine’s efficiency increases with temperature
- CSP efficiencies are around 30%

CSP technologies

Parabolic trough

- Parabolic trough system consists of a linear parabolic reflector that concentrates light onto an absorber tube in the focal line of the mirror
- Inside the absorber tube is the working fluid
- Fluid is heated and pumped into the steam generator (heat exchanger), connected to a steam turbine generator to produce electricity
- Working fluid is cycled back through the solar collector field to repeat the cycle

Figure 6-3: Parabolic troughs.

CSP technologies

Parabolic trough

- Synthetic oil or molten salt is used as heat transfer fluid, temperature reaches up to 400°C
- Absorber tube is made of steel with black coating and surrounding protective glass
- Space between glass and tube is evacuated to reduce heat loss
- Parabolic surface is coated glass mirrors or polished aluminum
- Aligned on north-south axis and Sun tracking in east-west direction
- May contain thermal energy storage

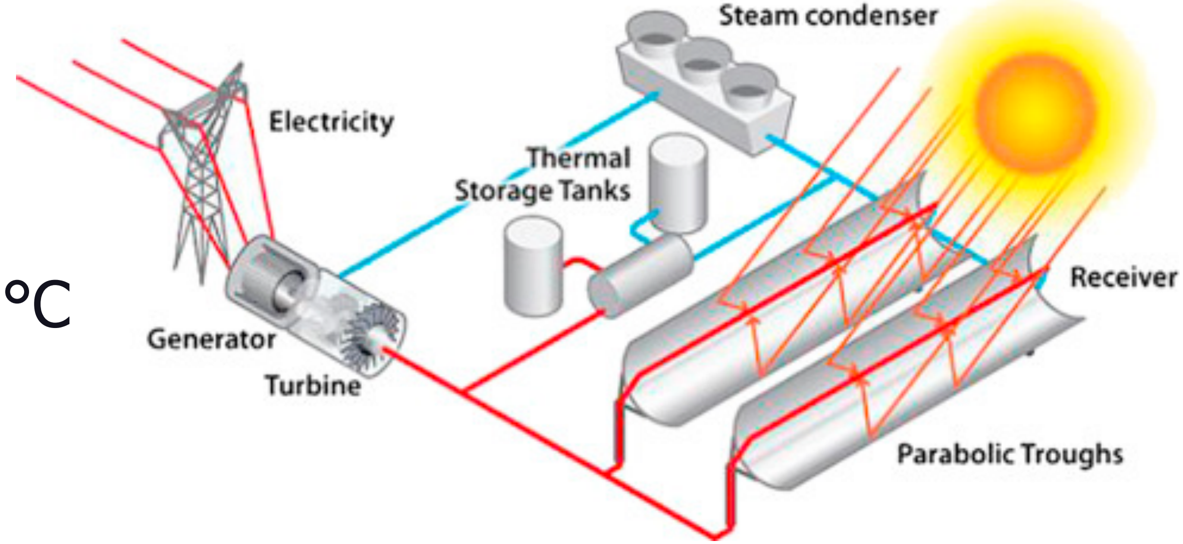


Figure 6-4: Parabolic trough system design.

- Thermal efficiency can range between 60-80%
- Overall efficiency, from collector to grid, is similar to PV ~15%

CSP technologies

Linear Fresnel reflector

- Linear Fresnel reflector (LFR) system uses long rows of flat or slightly curved mirrors
- Mirrors rotate to track the Sun and reflect direct sunlight onto a linear receiver that faces downward
- Based on Fresnel lens, where thin lens fragments are combined to simulate the effect of a thicker conventional lens
- Linear receiver is located at the common focal point of the reflectors and is fixed

Figure 6-5: Linear Fresnel reflectors.

CSP technologies

Linear Fresnel reflector

- Heat is transferred to the working fluid in an absorber pipe at the receiver and is converted to steam to drive the turbine
- Working fluid is usually water or oil
- Receiver can have a secondary parabolic reflector on top
- Receiver can consist of one or several tubes with the heat transfer fluid (HTF) and they can be contained in a vacuum glass tube enclosure

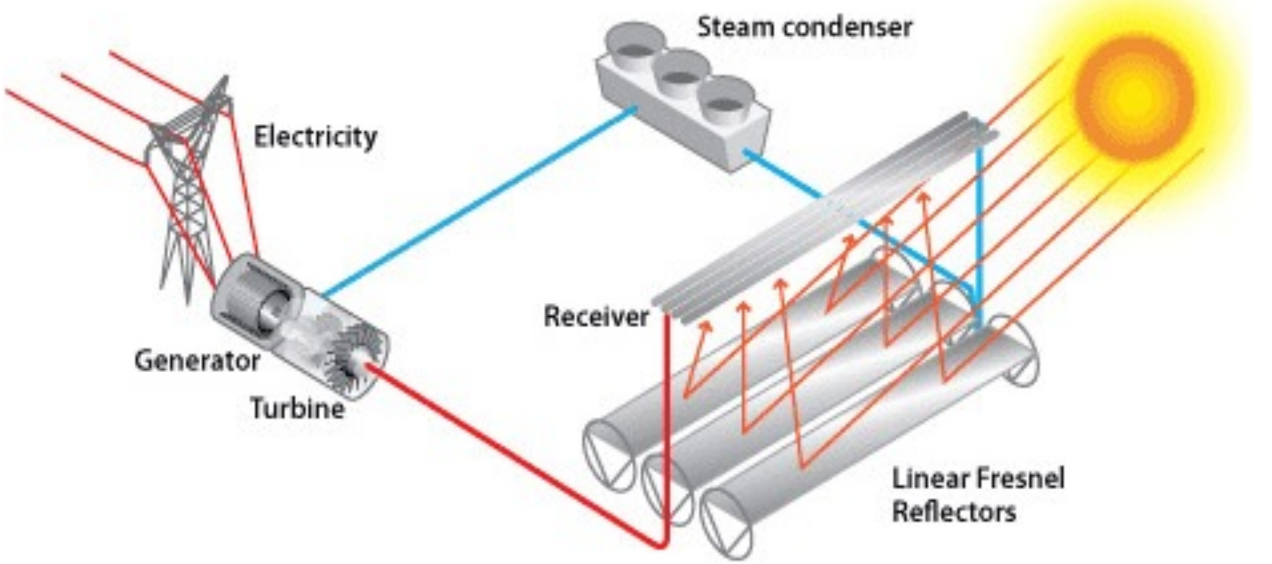


Figure 6-6: Linear Fresnel reflector system design.

CSP technologies

Linear Fresnel reflector

- Optical efficiency can reach up to 70%, lower than parabolic trough (up to 80%)
- LFRs have lower costs than curved glass parabolic reflectors
- LFR system requires 1/3 of land compared to parabolic trough of same installed power
- Shading effects due to several rows of mirrors using the same receiver
- Compact linear Fresnel reflector (CLFR) uses multiple parallel receivers elevated on towers

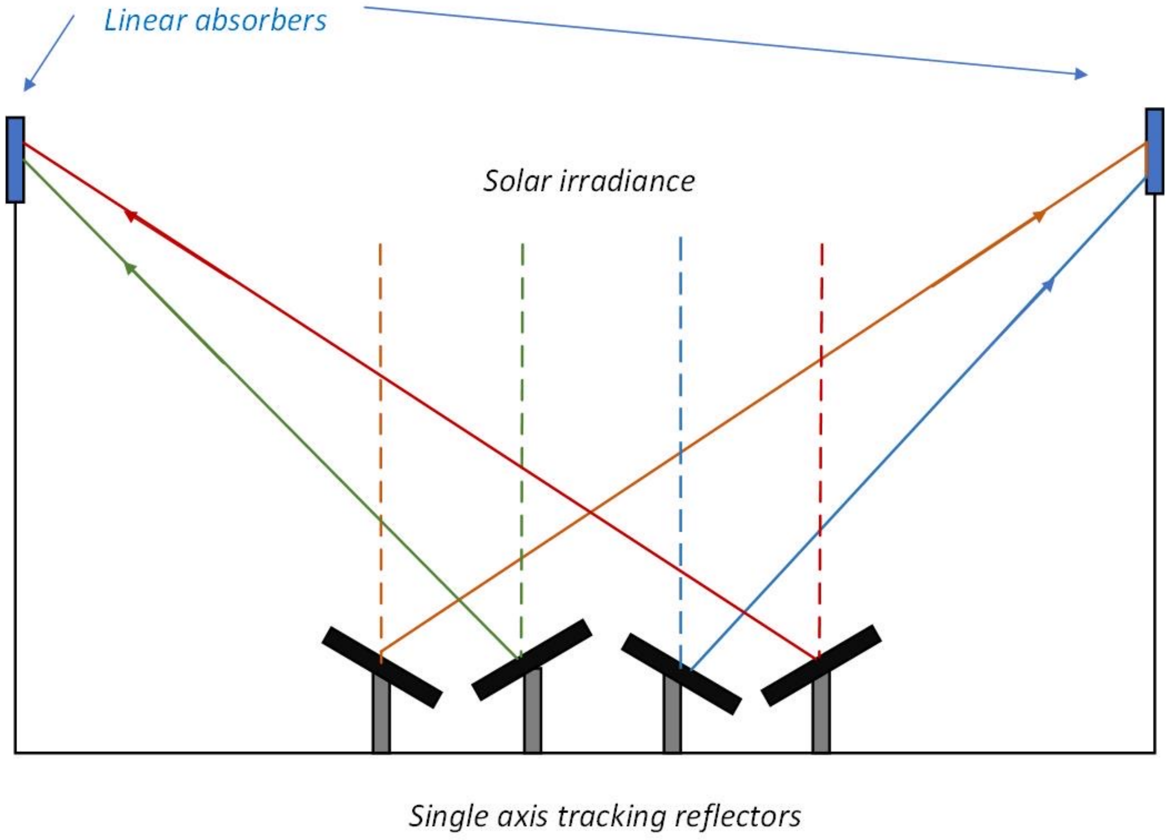


Figure 6-7: Compact linear Fresnel reflector.

CSP technologies

Parabolic dish/engine

- Dish/engine systems use mirrored parabolas to concentrate light onto a receiver, at the dish focal point. Can track Sun in two axes
- Working fluid in the receiver can be heated up to 700°C before being used to drive a heat engine
- Heat engine is usually a Stirling cycle engine, which is externally heated
- It has a receiver with thin tubes containing hydrogen or helium gas, which run on the outside of the four piston cylinders of the engine and open into them

Figure 6-8: Dish Stirling system.

CSP technologies

Parabolic dish/engine

- Gas is heated at high temperatures and expands inside the cylinders, driving the pistons, which drive the electric generator
- Receiver, engine and generator are mounted as an assembly at the dish focal point
- High optical efficiency, small area for thermal losses
- No water requirement for cooling
- Many modules working together require large land areas to avoid shading effects
- Most efficient of all solar power technologies ~30%

CSP technologies

Solar power tower

- A solar power tower system (central receiver system) uses heliostats to track the Sun
- Heliostats reflect sunlight onto a central receiver, installed at top of a tower
- Working fluid is heated at the receiver, at 500-1000°C and is lead to storage or a power conversion system to convert thermal energy to electricity

Figure 6-9: Solar power tower.

CSP technologies

Solar power tower

- HTF can consist of water/steam or molten salt
- Power tower systems have high efficiencies in energy collection and conversion and capability of energy storage with molten salt tanks
- When using water/steam as HTF, tower can produce steam directly and thermal-to-electricity conversion efficiency is higher
- When using molten salt as HTF, there’s efficient thermal energy storage for several hours

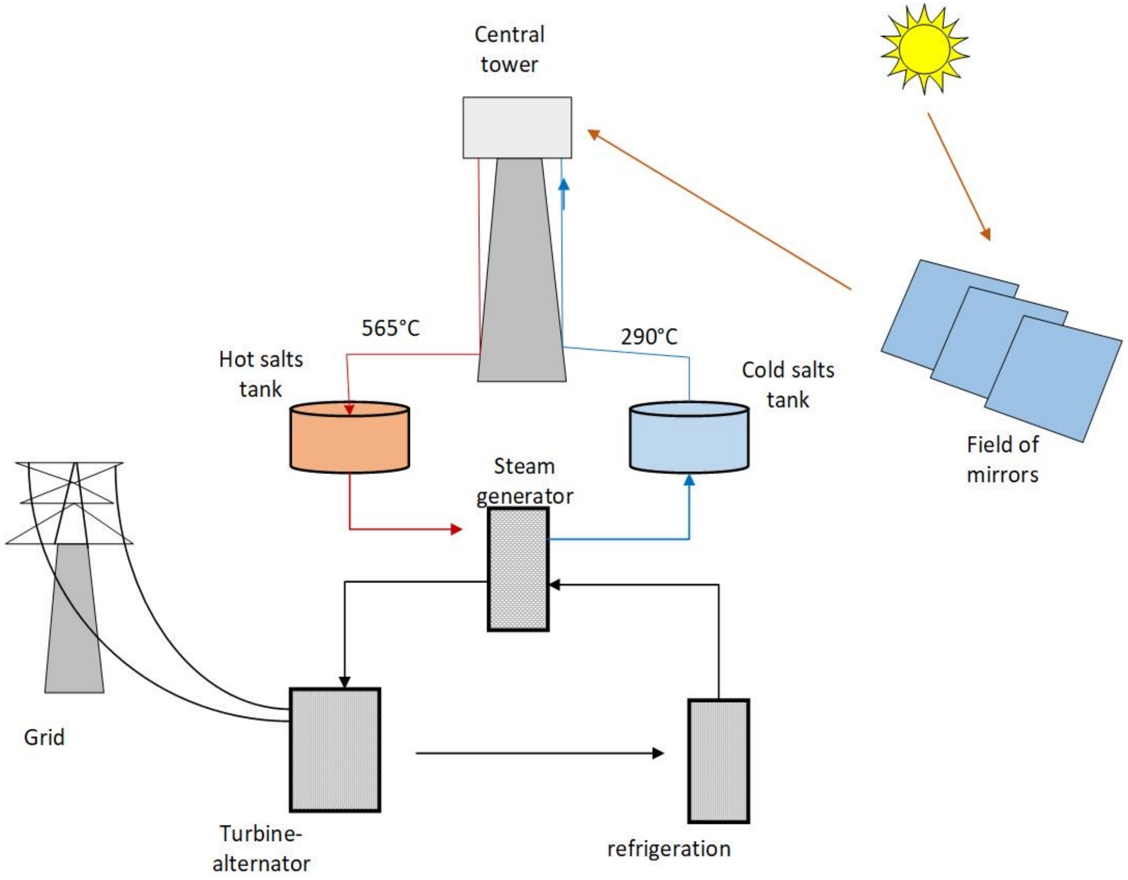


Figure 6-10: Solar tower system design with energy storage.

Thermal energy storage

- Thermal energy storage (TES) in CSP systems allows for power use during cloudy conditions or at night
- Thermal energy can be stored in media like molten salt, phase-change materials, concrete etc.
- TES systems are divided in three types: sensible heat, latent heat and thermochemical storage
- Parameters that characterize a TES system: storage capacity, rates of heat input and output during charging and discharging processes, storage efficiency (ratio of energy that is provided to the energy required to charge system), storage period, overall cost

Thermal energy storage

Sensible heat storage

- Sensible heat storage (SHS) is the simplest way to store thermal energy
- SHS is achieved by heating or cooling a liquid or solid storage medium
- Medium can be water, molten salt, rock or others
- In solid medium, heat is stored and extracted by means of gas or liquid flow through the pores or voids of the material
- Amount of heat stored (Q_s) depends on medium's specific heat (c_p), change in temperature and mass of storage medium (m)

$$Q_s = m * c_p * (t_f - t_i)$$

- t_i and t_f : initial and final temperatures

Thermal energy storage

Sensible heat storage

Water tank storage

- Water has high specific heat, popular storage medium
- Majority of solar water heating and space heating systems have hot water tanks for storage
- Tanks can range from few hundred liters to several thousand cubic meters
- Charging temperatures of water are around 80-90°C
- Difference in temperature can be enhanced by using heat pumps for discharging

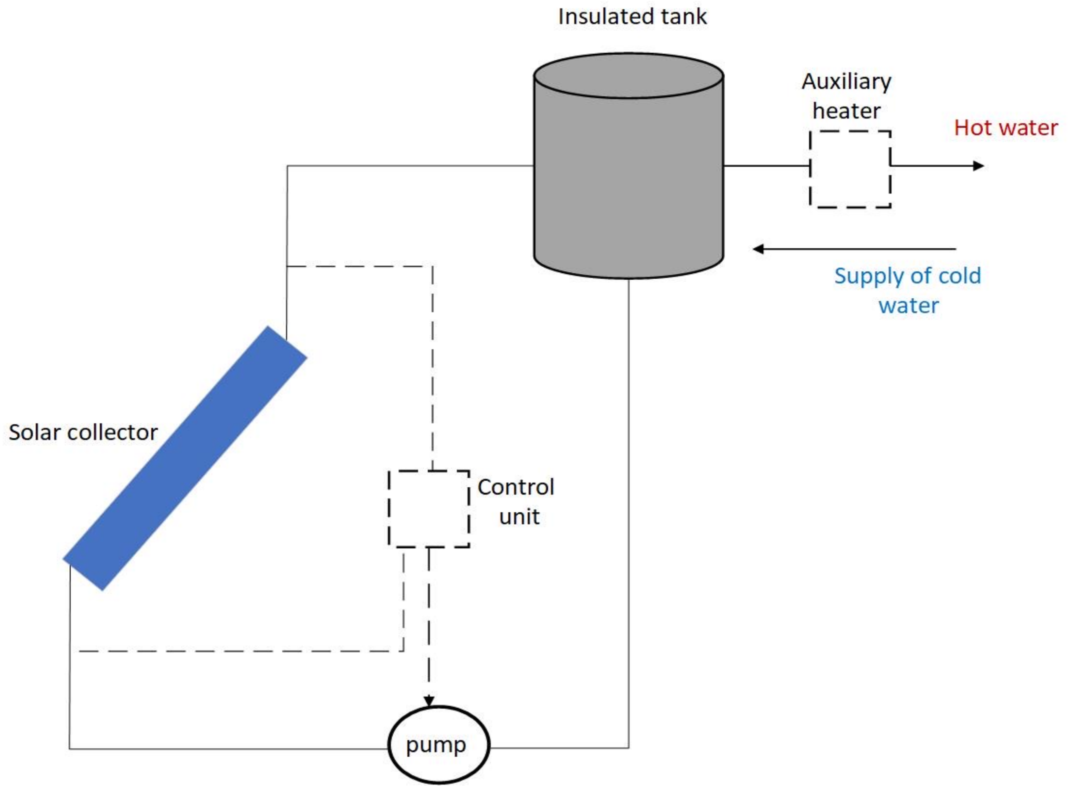


Figure 6-11: A water tank storage system.

Thermal energy storage

Sensible heat storage

Underground storage

- ○ Underground storage uses rocks, sand, soil as storage medium
- ○ HTF is pumped in the ground through pipes buried in horizontal trenches or inserted vertically in boreholes
- ○ Charging and discharging depends on pipes length and heat transfer rate through ground
- ○ In aquifer storage, hot water is pumped into aquifer for storage, displacing the cold ground water that exists

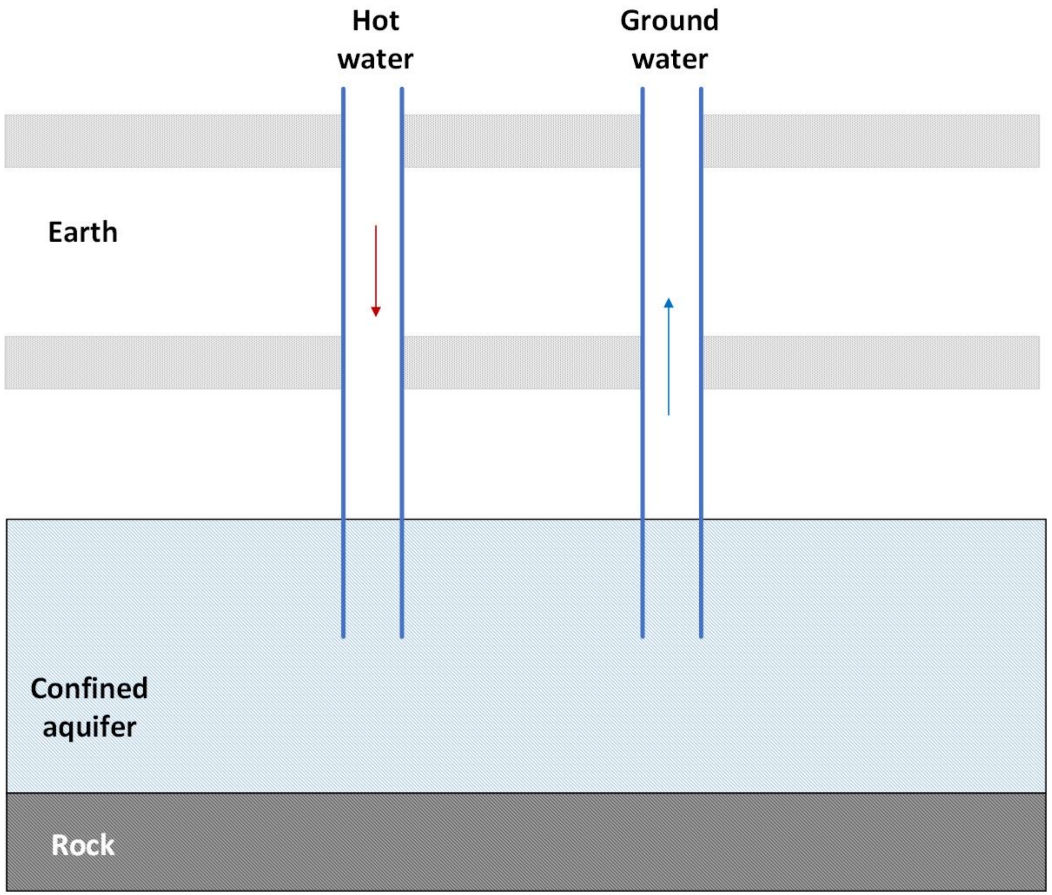


Figure 6-12: An underground aquifer storage system.

Thermal energy storage

Sensible heat storage

Underground storage

- Other underground storage systems are the cavern and pit storage, based on large underground reservoirs of water
- The reservoirs are located in the subsoil
- High cost systems
- Water can be used as storage medium for temperatures up to 100°C.
- Higher than 100°C, oils and molten salt are commonly used
- For very high temperatures, solid medium is used (ceramics, concrete etc.)

Thermal energy storage

Sensible heat storage

Pebble-bed storage

- ○ The pebble-bed storage system is based on heat storage in solids
- ○ It uses the heat capacity of a bed of loosely packed particulate material (rocks, pebbles) to store heat
- ○ A fluid (air) circulates through the bed so energy is added/removed
- ○ Heat is added with the flow usually downward and is removed with the opposite flow. Can't happen simultaneously
- ○ High degree of stratification, when fully charged temperature is uniform

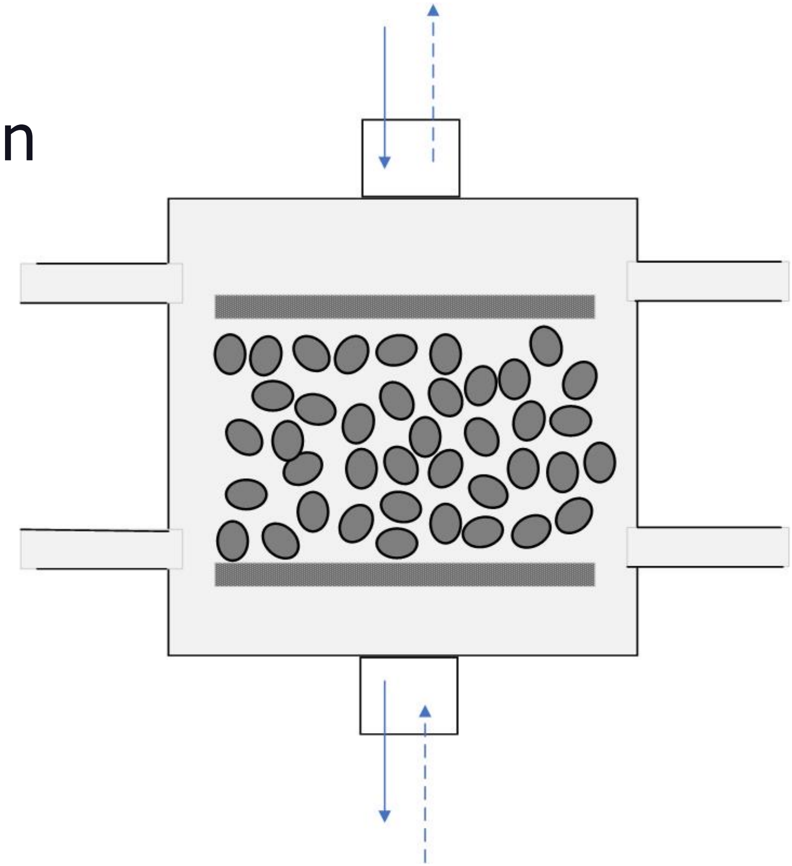


Figure 6-13: A pebble-bed storage system.

Thermal energy storage

Latent heat storage

- Latent heat storage (LHS) systems are based on the phase change of a material when heat is applied to it (no change in temperature)
- Change can be from solid to liquid when storing heat as latent heat of fusion or from liquid to vapour when storing the heat as latent heat of vaporization
- When stored heat is extracted, phase will change back

$$Q_s = m * \left[c_{ps}(t_m - t_i) + f\Delta q + c_{pl}\left(t_f - t_m\right)\right]$$

- Q_s: storage capacity, m: mass, c_{ps}: average specific heat of the solid phase between t_i and t_m, c_{pl}: average specific heat of the liquid phase between t_m and t_f, t_m: melting temperature, f: melt fraction, Δq: latent heat of fusion

Thermal energy storage

Latent heat storage

- Solid-liquid transition mostly used, it has high latent heat and small volume changes
- Process of melting can have energy densities up to 100 kWh/m^3 (e.g. ice), while the equivalent for a SHS system is typically around 25 kWh/m^3
- Phase change materials (PCM) can be used for daily or seasonal energy storage
- Higher investment costs
- LHS system should have a suitable PCM in desired temperature range, a container for storage material and a suitable HTF
- Popular PCMs: organic (parafin compounds, fatty acids), inorganic (hydrated salts). For cold storage, water/ice is used as well

Thermal energy storage

Latent heat storage

Containment of PCMs

- Containment of PCMs can be done with bulk storage in tank heat exchangers, macro-encapsulation or micro-encapsulation
- Macro-encapsulating is most common, PCMs are kept in a tube, sphere or cylinder, plastic or metal
- Micro-encapsulating consists of micro-spheres of PCM, encapsulated in a thin polymer of high molecular weight
- Capsules can be in a one tank TES system, where heat is transferred to a HTF as it flows between the capsules
- PCM in the capsules absorbs heat and turns into liquid (charging)
- Cool HTF circulates though tank and absorbs heat from PCM which freezes (discharging)

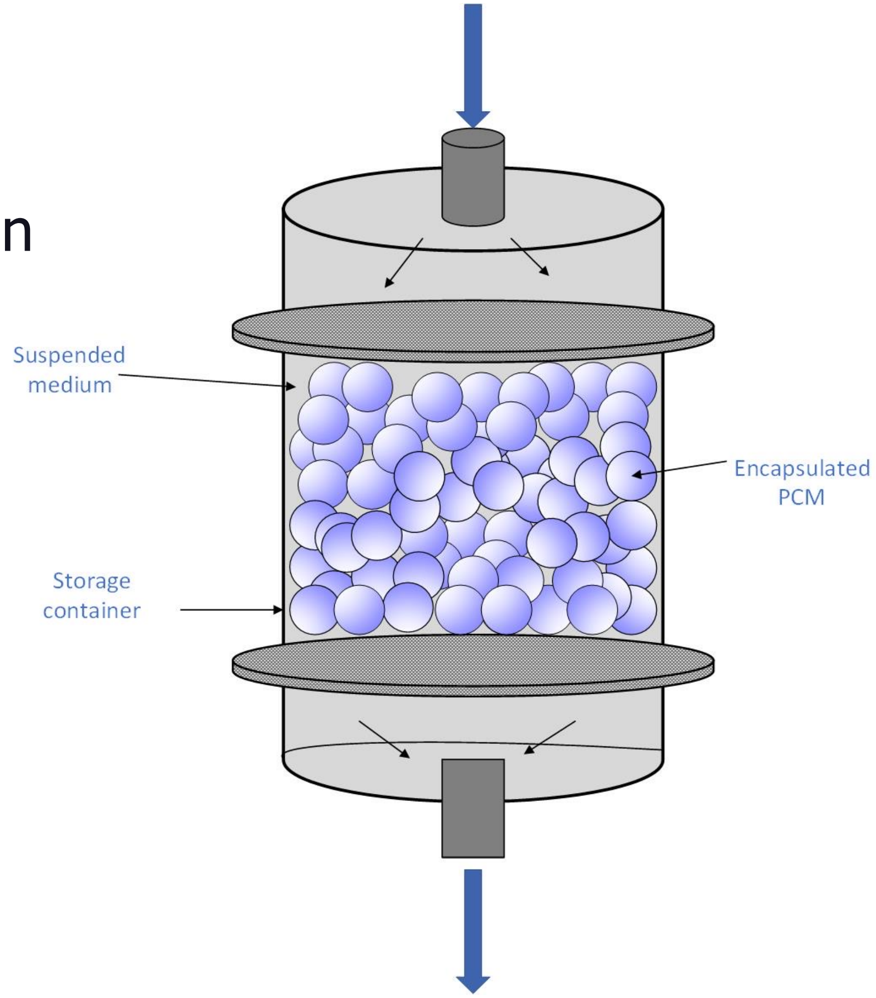


Figure 6-14: A direct contact TES system.

Thermal energy storage

Thermochemical storage

- Thermochemical storage is done by means of endothermic/exothermic chemical reactions. Tested for development
- Salt hydrate technology uses the reaction energy created when salts are hydrated and dehydrated
- Heat from collector evaporates water in sodium hydroxide (endothermic)
- Addition of water releases back heat (exothermic)
- Dried salt can be stored for prolonged time periods, suitable for seasonal storage
- Possibility of transport of stored dried salt
- High storage densities with minor thermal losses

Thermal energy storage

TES for CSP systems

- TES can be coupled with CSP system. In absence of sunlight, HTF flow is reversed, fluid is heated to drive the steam generator
- TES system should have high energy density or heat storage capacity
- Stable storage medium to avoid degradation after several cycles
- Must have good heat transfer between HTF and storage medium and good compatibility between them and the heat exchanger
- Process must be completely reversible, thermal losses minimum
- CSP installations mainly use two-tank and single-tank storage systems

Thermal energy storage

TES for CSP systems

Two-tank system

- Two-tank direct system
- Fluid is stored in two tanks, one at high and one at low temperature
- Fluid from low temperature tank flows through collector, gets heated, flows to high temperature tank for storage
- When needed, fluid from high temperature tank flows through a heat exchanger to generate steam for electricity production
- When it exits heat exchanger, it's at a low temperature and flows back to low tank

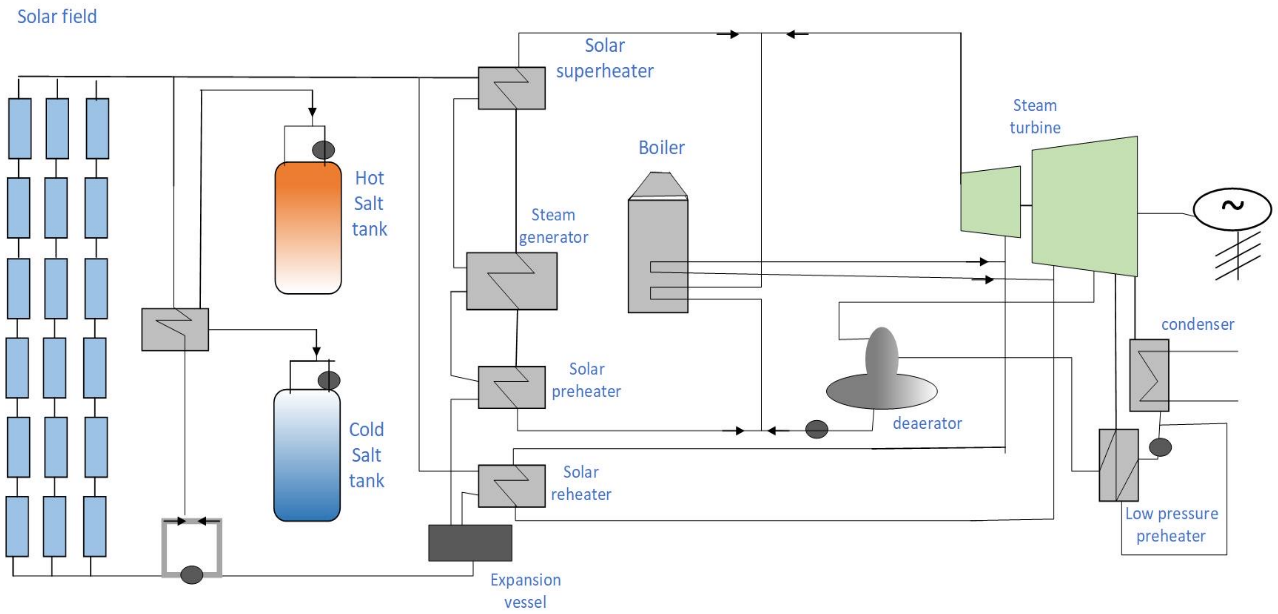


Figure 6-15: A two-tank molten salt thermal storage system.

Thermal energy storage

TES for CSP systems

Two-tank system

- In two-tank indirect system, two fluids are used, one for heat transfer and one for storage
- Indirect system is good for installations where HTF is expensive or not suitable for storage
- Storage fluid in low tank flows through an extra heat exchanger, gets heated with the help of high temperature HTF
- Storage fluid then flows to high temperature tank
- HTF exits heat exchanger at low temperature and flows back to collector to repeat cycle
- Can use oil as HTF and molted salt as storage fluid

Thermal energy storage

TES for CSP systems

Single-tank system

- Single-tank system (mainly thermocline) stores energy in solid medium in a single tank
- Medium is usually silica sand
- In thermocline system, top part of medium is always at high temperature, bottom at low
- High and low parts are separated by a thermocline (temperature gradient)

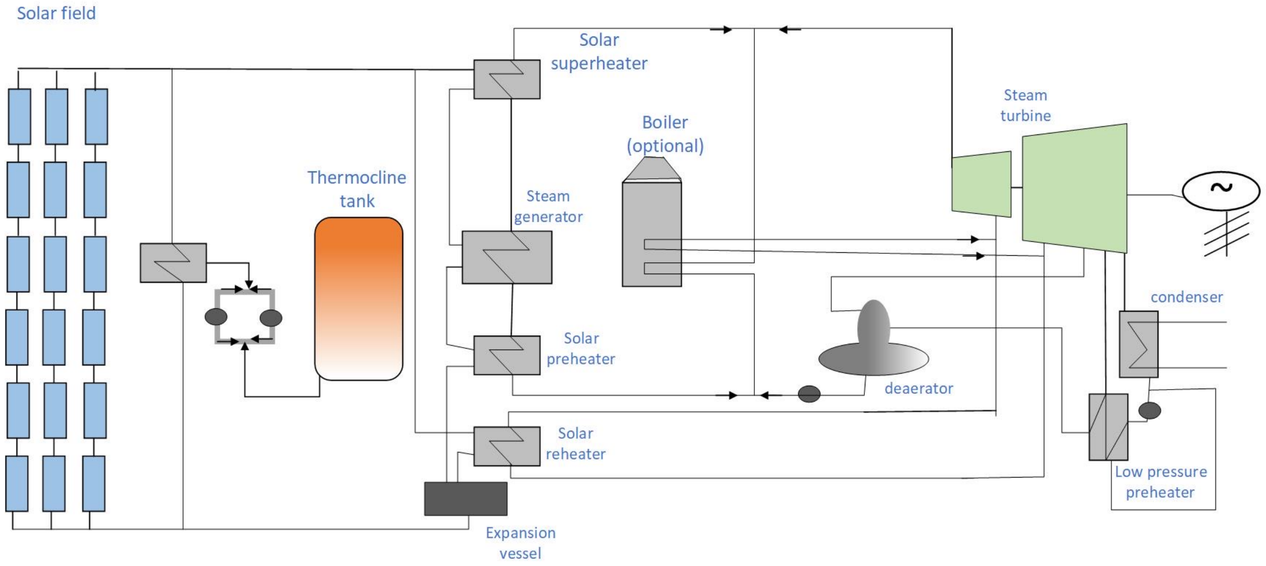


Figure 6-16: A single-tank (thermocline) thermal energy storage system.

Thermal energy storage

TES for CSP systems

Single-tank system

- HTF of high temperature enters thermocline at top, leaves at bottom at low temperature
- Thermocline is moved downwards, thermal energy is added to the system for storage
- When flow is reversed, thermocline moves upwards, thermal energy is removed
- Thermal stratification of fluid in the tank is due to buoyancy effects and thus thermocline is stabilized and maintained
- Reduced costs with this system

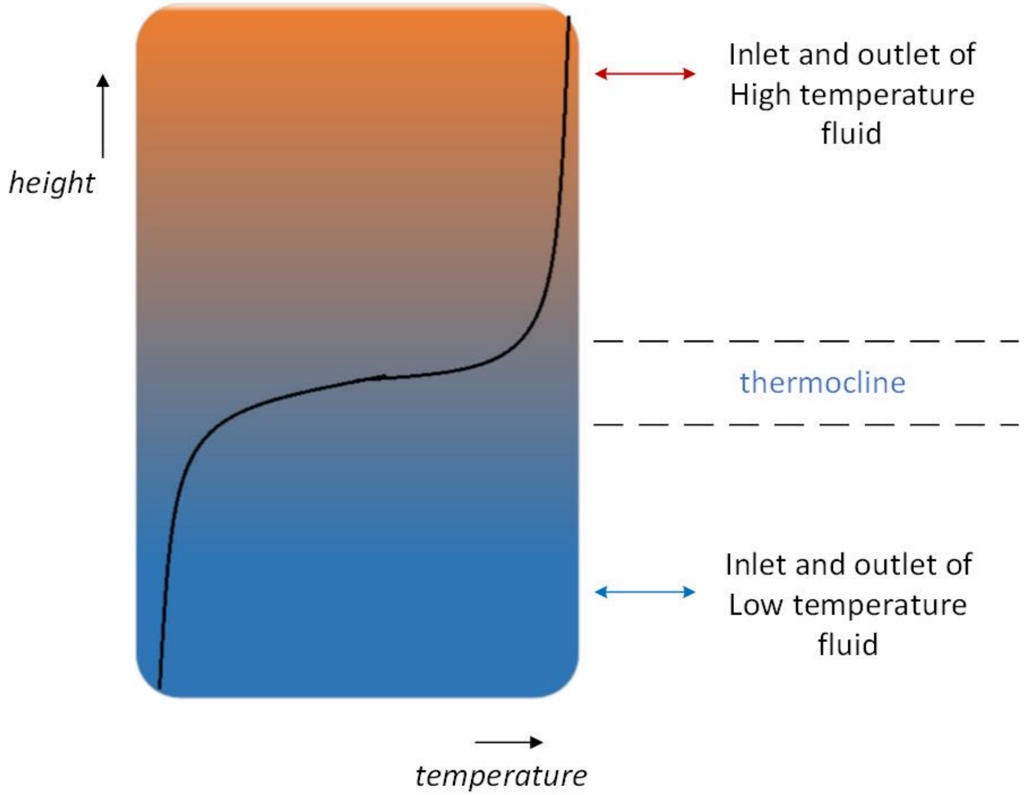


Figure 6-17: Schematic of thermocline energy storage.

Solar water heating

- Solar water heating (SWH) is the process of heating water with use of solar thermal collector
- In passive SWH system, working fluid circulation is based on convection or heat pipes
- Active systems use pumps to circulate the working fluid
- In a direct system (open loop), potable water circulates through collectors
- Indirect (closed loop) systems use heat exchanger to transfer heat from HTF to potable water
- Active systems are more efficient and expensive, used for high load demand
- Passive systems are simpler and have lower costs, usually used in applications with low load demand

Solar water heating

Passive water heater

- Passive water heater doesn’t use pumps to circulate water
- Water circulation is achieved by means of gravity and convection
- Thermosyphon: tank located above collector, circulation by natural convection
- Medium is heated in the collector, rises to tank top, cools down and flows back to the bottom of collector
- Hot water is taken directly from tank or indirectly via a heat exchanger

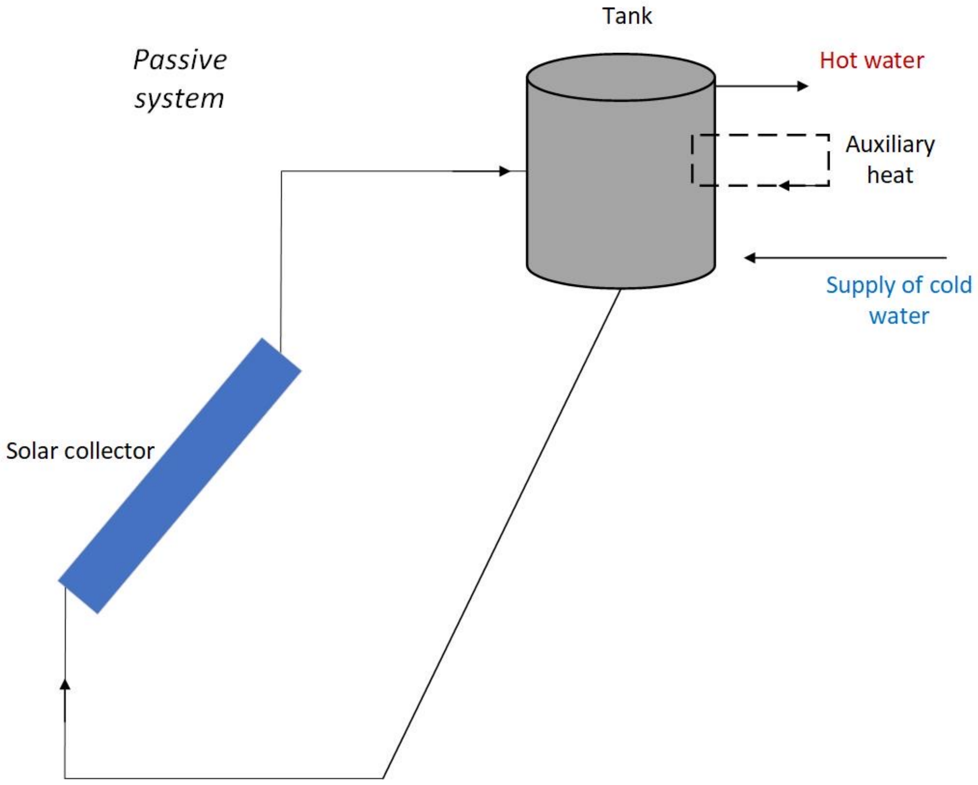


Figure 6-18: A passive SWH system.

Solar water heating

Passive water heater

- Thermosyphon is simple and cost effective
- Auxiliary power can be added to the water at top of tank to maintain efficient hot water supply
- An integrated collector storage (ICS) system uses a tank as both a collector and storage
- Consists of a thin rectilinear tank with a glass side that faces Sun at noon
- More efficient in locations with good weather conditions as system has high heat losses
- Modern versions have tank enclosed in insulation box with layers of glazing

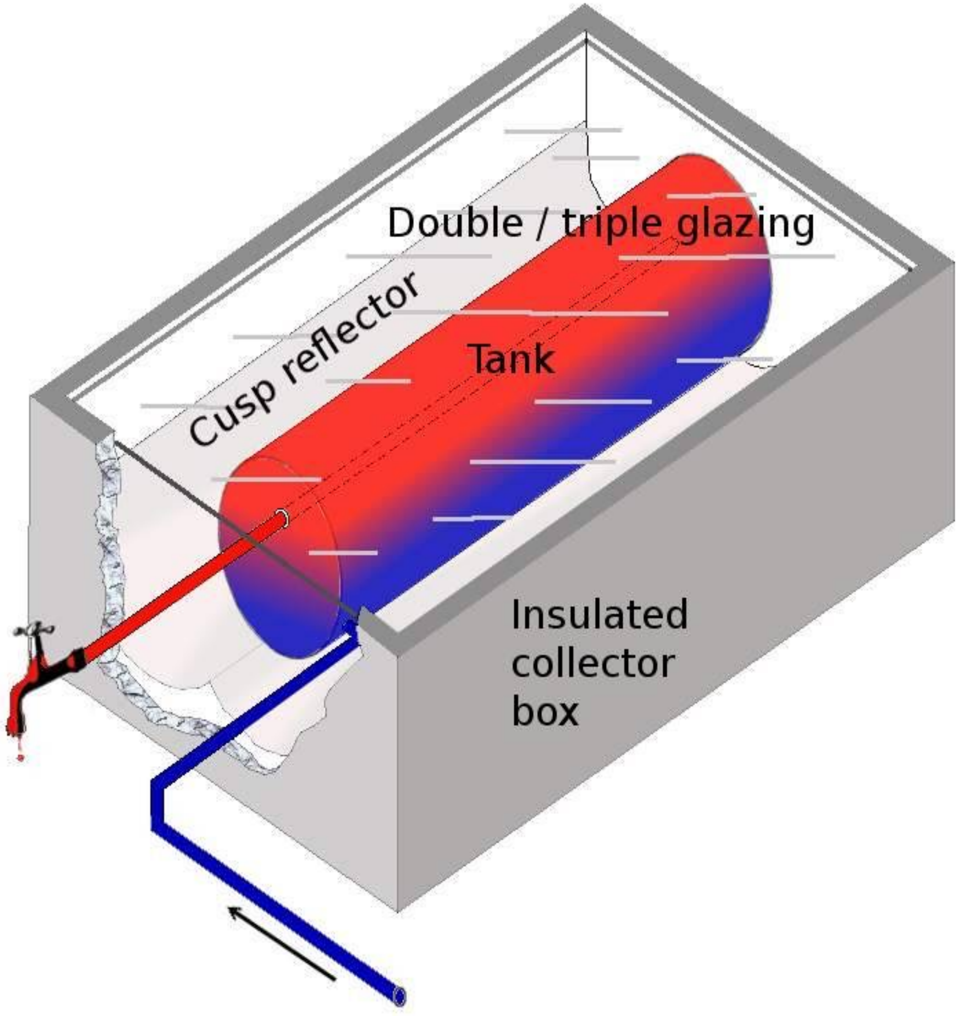


Figure 6-19: An ICS system.

Solar water heating

Active water heater

- Differential thermostat turns on the pump when temperature at the top header is higher than water temperature at bottom of the tank
- Check valve is used to prevent reverse circulation and thermal losses from collector at night
- In direct system, water runs through collector. Suitable for places with no extended freezing conditions or hard water
- Lower costs among active SWH systems
- High operating performance, no heat losses at night

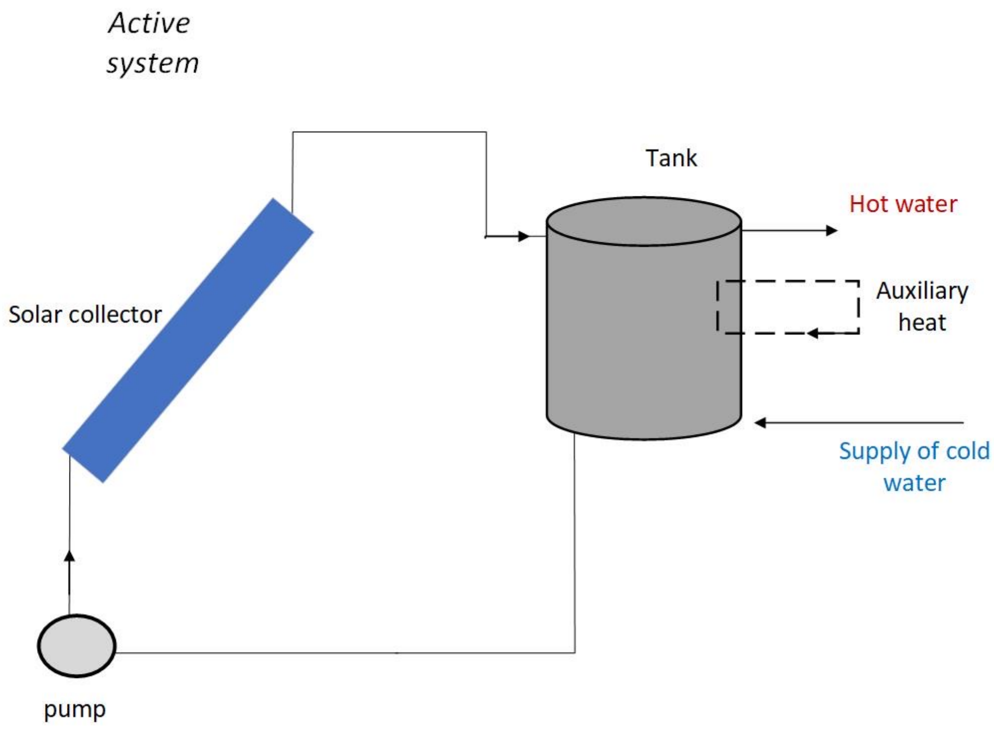


Figure 6-20: An active SWH system.

Solar water heating

Active water heater

- In indirect system, HTF heats water in tank via a heat exchanger
- Active indirect systems use a mixture of glycol and water antifreeze as HTF to prevent damage in freezing conditions
- This non-freezing fluid is circulated with pumps through collector and heat exchanger
- Used in cold climates, antifreeze recharge (2-3yrs)
- System more complex

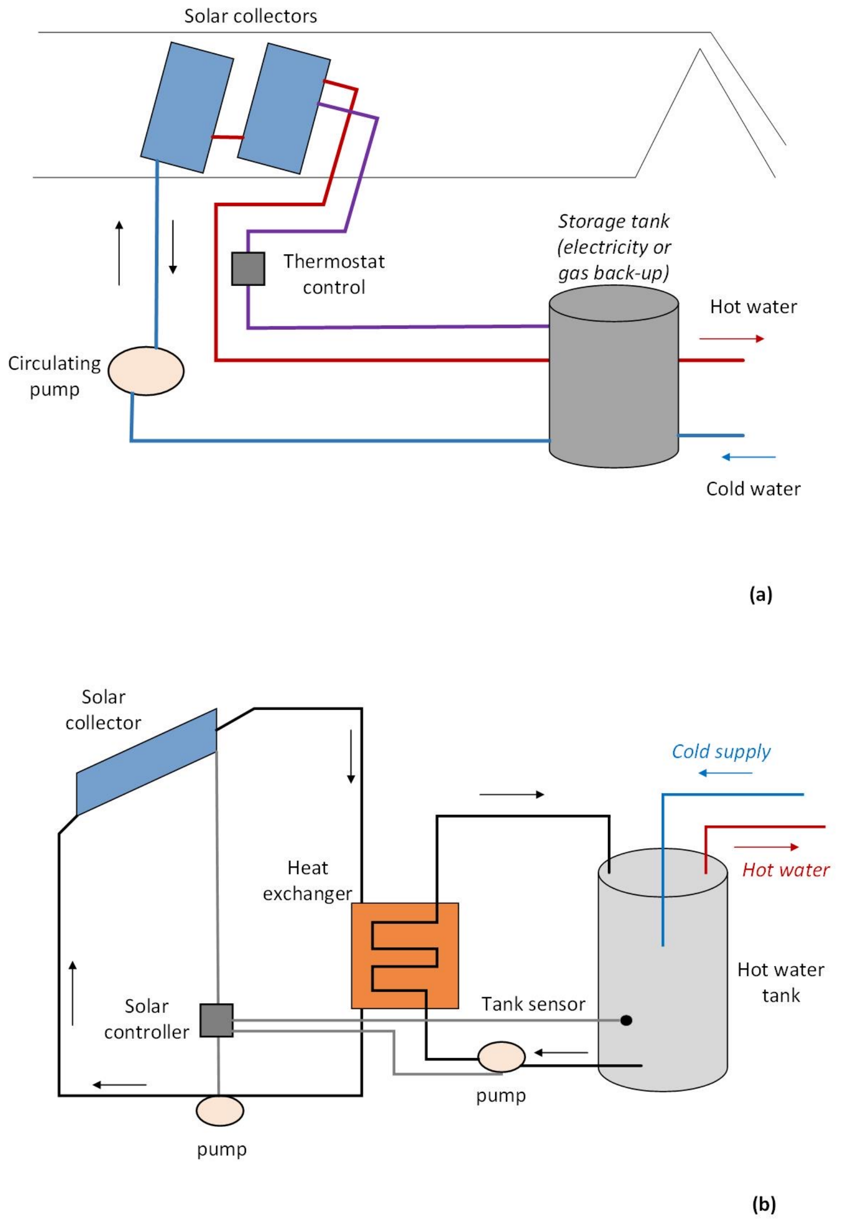


Figure 6-21: (a) An active direct and (b) an active indirect SWH system.

Solar water heating

Active water heater

- Drain-down system is a modification of active direct system
- Collector is filled with domestic water under supply pressure when there's no freeze
- A differential controller operates a pump to move water from tank through the collector
- A drain-down valve protects from freeze. When activated, collector's inlet and outlet are isolated from tank and water in collector is drained away
- Vacuum breaker at collector top so air can enter and water can be drained at bottom

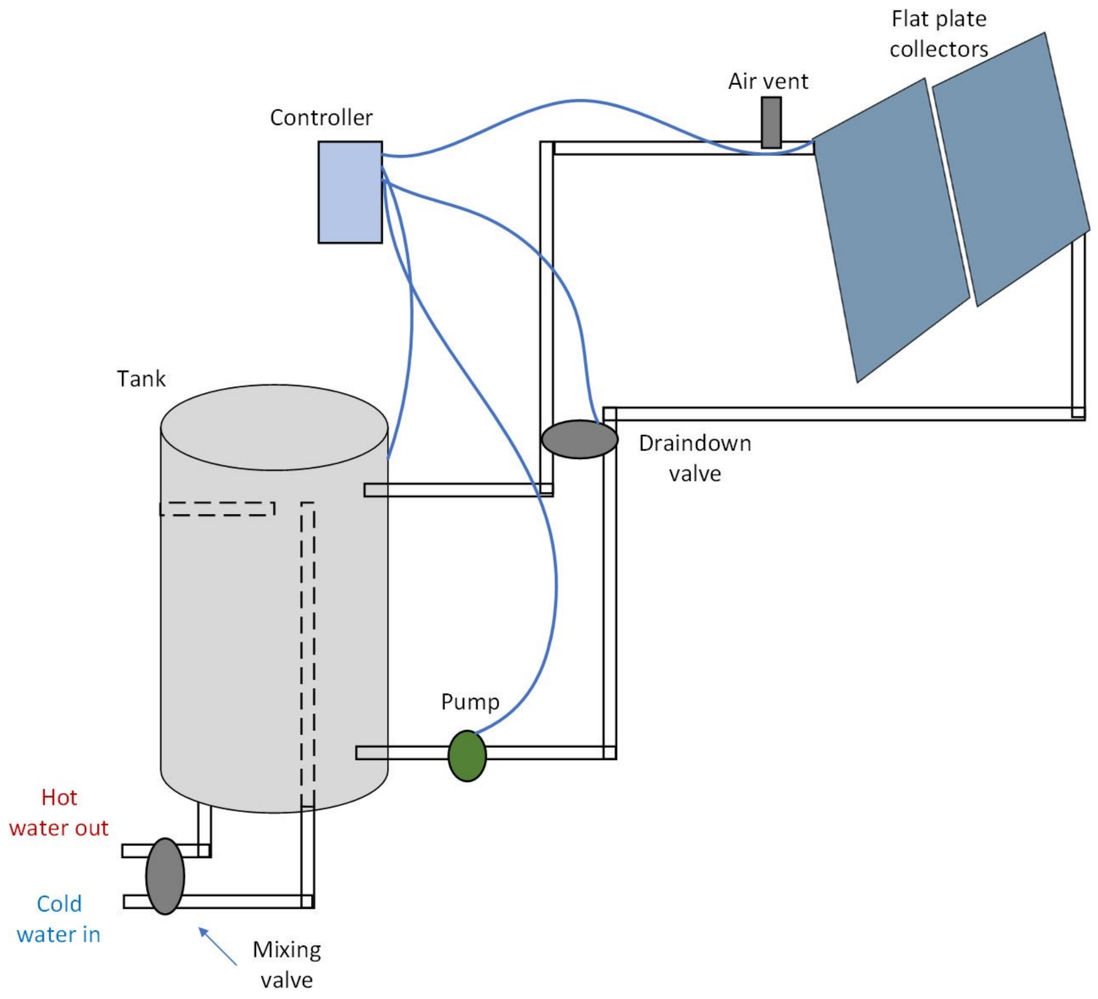


Figure 6-22: Design of a drain-down SWH system.

Solar water heating

Active water heater

- A drain-back system is a modified active indirect system, not pressurized, that uses pumps to circulate water, used as HTF, through the collector
- When pumps are not activated, water in collector loop is drained into a reservoir
- Heat exchanger transfers heat from collected water to domestic water
- No freezing or overheating, no need to change HTF after a few years
- Another version of an active indirect system is the air system, where air is used as the working fluid
- A fan circulates air through the tubes and heat exchanger, which transfers heat from air to water in a horizontal tank
- Noncorrosive, low maintenance system, no freezing or overheating, takes up large area because of air unit

Solar water heating

Solar thermal collectors

Flat-plate collector

- Flat-plate collector consists of an absorber plate inside an enclosure, with transparent cover sheets to allow energy transmission
- Absorber material must have high thermal conductivity, e.g. copper, aluminum and it has tubes for circulation
- HTF (water or antifreeze) circulates through tubes to remove heat from absorber
- Heat exchanger transfers heat from collector fluid to water in the storage tank

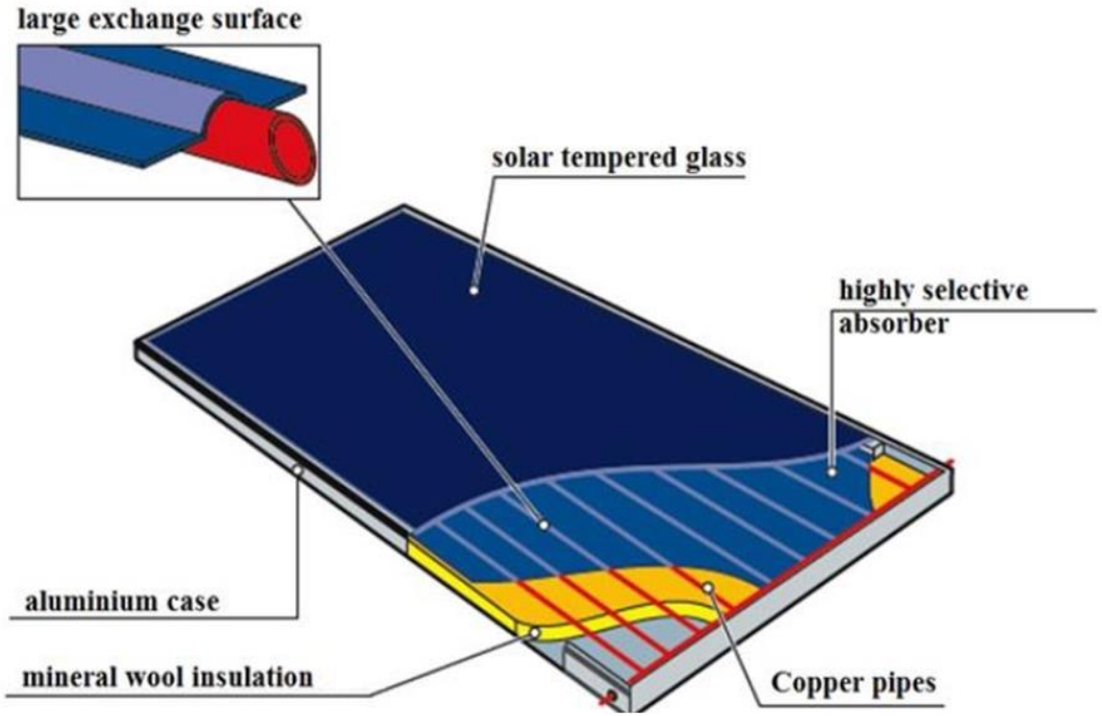


Figure 6-23: Flat-plate collector.

Solar water heating

Solar thermal collectors

Flat-plate collector

- Absorber is coated with selective material to maximize energy absorption while minimizing emission
- Usual tube layout is parallel with bottom pipes risers and top collection pipe but temperature distribution is not uniform in absorber surface, not equal distribution of working fluid in collector risers
- A serpentine configuration can be used, with a continuous s-shaped pipe
- This allows total mass flow rate to pass through the tube and increases heat transfer coefficient and thermal performance

Solar water heating

Solar thermal collectors

Evacuated-tube collector

- Evacuated tube collector is made of several rows of transparent glass tubes, connected in parallel
- Glass tube surrounds absorber with high vacuum
- Absorber can be metallic or a second concentric glass tube
- HTF flows in and out of the tube or is in contact with a heat pipe inside the tube
- Heat pipe transfers heat to the fluid in a heat exchanger (manifold), placed transverse to the tube

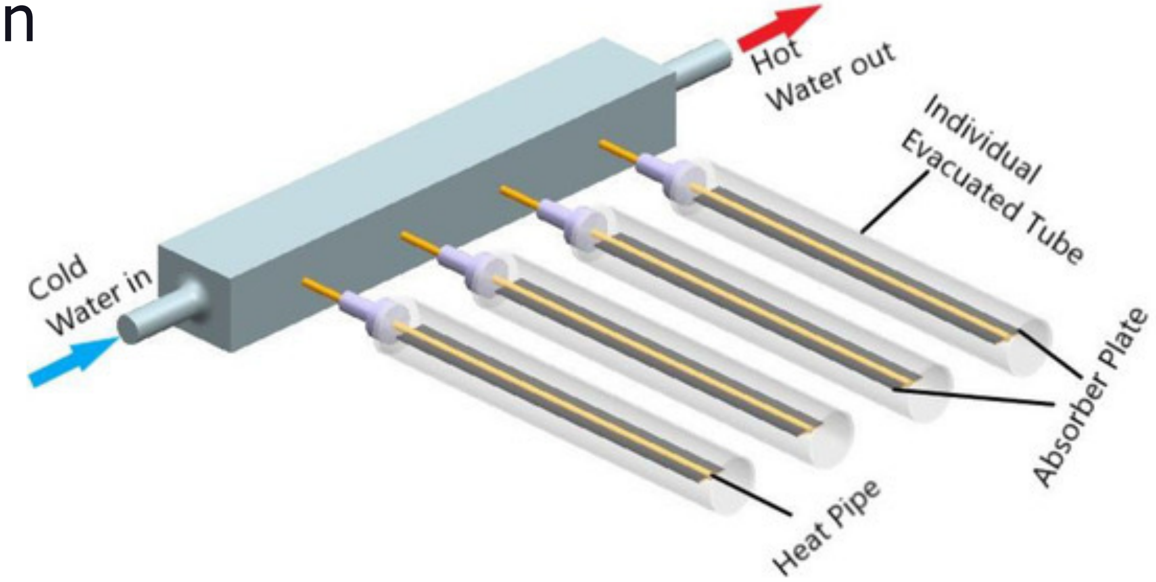


Figure 6-24: Evacuated tube collector.

Solar water heating

Solar thermal collectors

Evacuated-tube collector

- Angle of sunlight is always perpendicular to the tube due to cylindrical shape
- Each tube has a thick glass outer tube and a thinner glass inner tube, made of borosilicate and with vacuum between them
- Inside tube is the aluminum or copper fin, flat or curved, connected to a metal heat pipe running the length of inner tube
- Absorber fin is covered with selective coating to transfer heat to fluid circulating through heat pipe
- Heat is transferred to manifold, connected to storage tank and heats water inside
- Good performance in cold weather, higher cost

Solar water heating

Solar thermal collectors

Evacuated-tube collector

- In U-tube or direct flow evacuated tube collector, there are two heat pipes running through tube center
- One is for the flow, other for the return
- Connection at the bottom of the tube forms a U shape
- More efficient because of direct flow design and absence of heat exchanger between fluids
- Not easy to replace tubes in case of damage

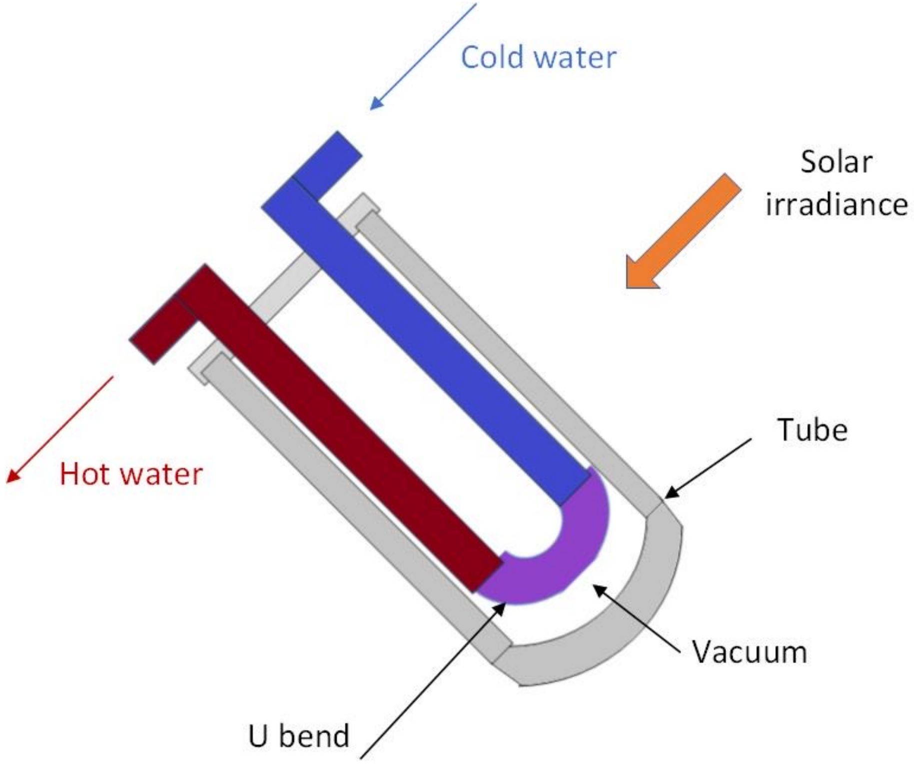


Figure 6-25: Direct flow evacuated tube collector.

Solar water heating

Solar thermal collectors

Concentrating collector

- Flat-plate and evacuated tube collectors are used for temperatures up to 120°C
- For higher temperatures, concentrating collectors are used
- Temperature level of concentrating collector depends on concentrating ration, C:

$$C = \frac{total\ concentrator\ aperture}{receiver\ surface}$$

- C<5, non-imaging collector, temperatures up to 200°C
- C>10, imaging collectors, temperatures up to 500°C

Solar water heating

Solar thermal collectors

Concentrating collector

- Types: parabolic trough (up to 400°C, 15<C<45), linear Fresnel (10<C<40), solar dish (C>100, very high temperatures)
- Compound parabolic concentrator is non-imaging collector, 1<C<5
- Can collect and focus direct and diffuse solar radiation, doesn’t require Sun tracking
- Tilt angle can be periodically adjusted
- Consists of tubular receiver, cost effective

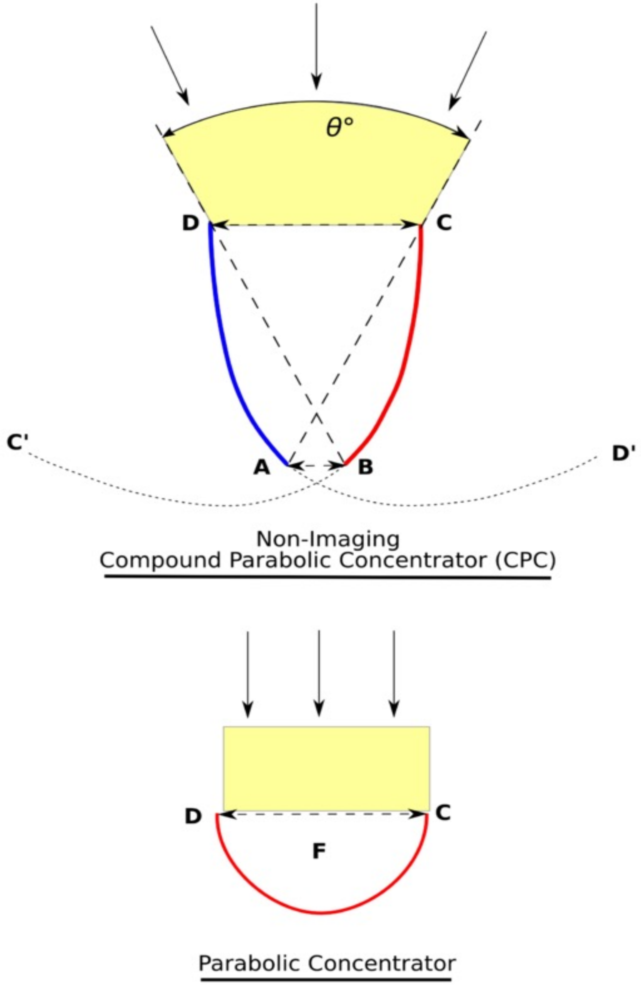
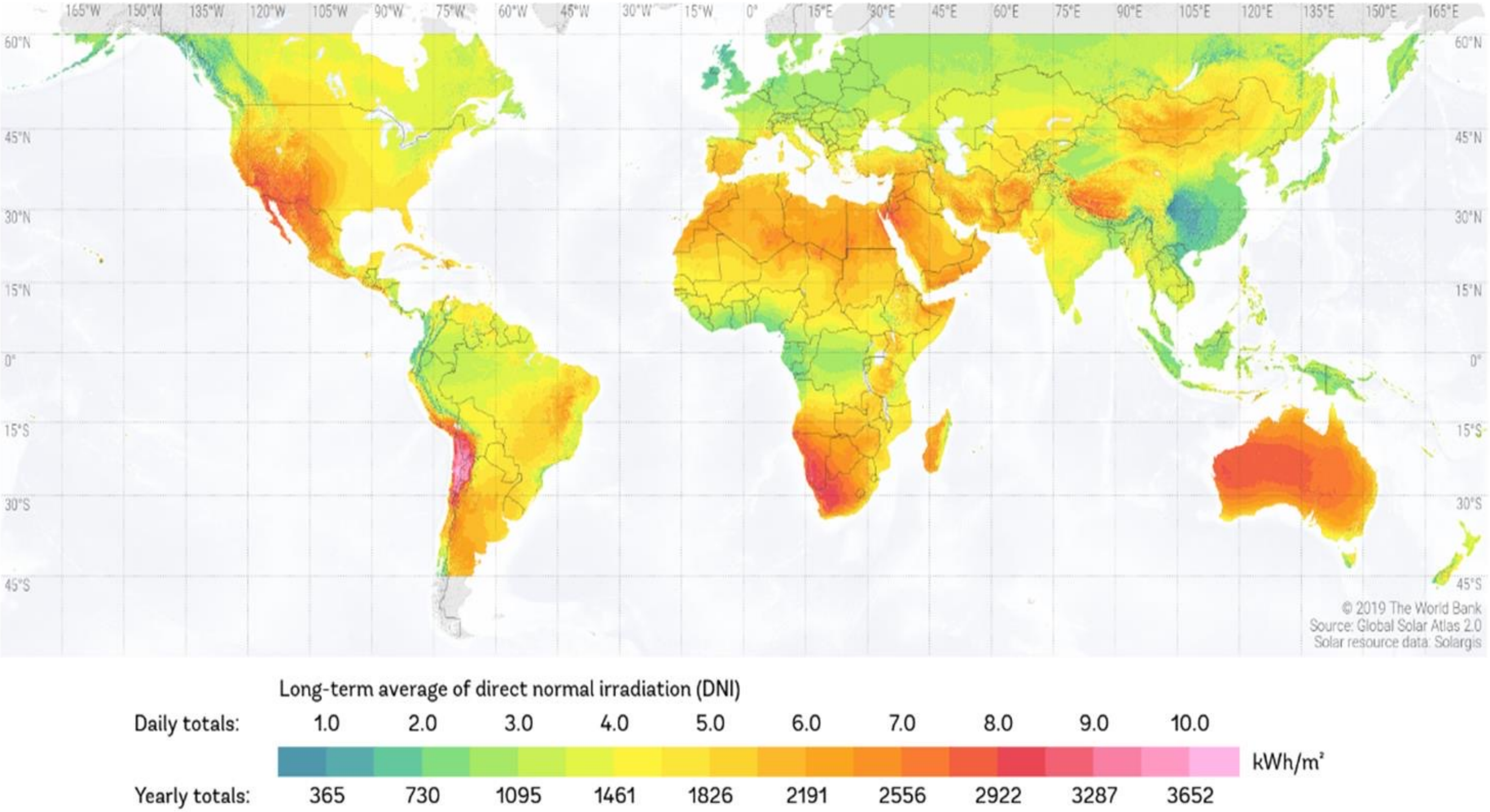


Figure 6-26: Comparison between a non-imaging compound parabolic concentrator (top) and a parabolic concentrator (bottom).

CSP system

Solar resource and forecast

- CSP systems require strong solar resource
- Direct Normal Irradiance (DNI) data determine a location’s suitability for CSP technologies



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

Figure 6-27: Distribution map of direct normal irradiation.

CSP system

Solar resource and forecast

- Forecast of DNI is vital. Various methods are used depending on the forecast horizon: time series analysis models (few minutes to one hour), satellite-based cloud motion vectors (few hours), numerical weather prediction models (several days)
- DNI forecast can’t be derived from global horizontal irradiance (GHI) forecast since atmospheric conditions have greater effect on DNI than on GHI
- Main factors that affect DNI are clouds and aerosols
- Clear Sky Models (CSMs) are based on irradiance annual cycle at one location and model it to determine Sun position. Complex CSMs model irradiance attenuation through atmosphere and include aerosol optical depth, ozone

CSP system

Solar resource and forecast

- Numerical Weather Prediction (NWP) models use atmospheric description at one time along with equations for horizontal/vertical momentum, energy conservation etc. to calculate changes in atmospheric conditions at fixed time steps
- NWP models can be global or mesoscale/regional
- Time Series Analysis (TSA) methods do statistical analysis of historical time series trends in parameters affecting forecast. The persistence model assumes future conditions will be the same as previous. Artificial Intelligence (AI) TSA models identify patterns recurring in time series. Can be produced with Artificial Neural Network (ANN)
- Cloud motion vector (CMV) is based on satellite or ground images to track cloud motion. Solar forecasts use CMV to predict future cloud cover and convert to solar irradiance with statistical and physical models

CSP system

Land and water

- CSP systems need significant land areas that can’t be used for other applications at the same time
- Collectors must be arranged so as to maximize concentrated solar energy and have enough space to avoid shading effects
- Land relatively flat, near transmission lines, not protective area
- Arid, semi-arid areas
- Water resource is important issue for CSP installations
- Large amounts of water are required for cooling, cleaning of mirrors

CSP system

Performance

- Efficiency of CSP system depends on technology type, operating temperature, thermal losses etc.

$$\eta = \eta_{optical} * \eta_{receiver} * \eta_{transport} * \eta_{storage} * \eta_{conversion}$$

- η_{optical} includes reflectivity losses, flux spillage losses until radiation reaches receiver
- η_{receiver} includes reflective losses from receiver, convective, conductive and radiative losses
- $\eta_{\text{transport}}$ includes thermal losses from pipes that lead HTF to storage or through power cycle and losses in heat exchangers between HTF and working fluid

CSP system

Performance

- $\eta_{storage}$ includes thermal losses due to storage device and losses in heat exchangers between HTF and storage medium and between storage medium and working fluid
- $\eta_{conversion}$ includes thermal, electrical and friction losses that take place in the power cycle
- Conversion efficiency of heat engine is limited by Carnot efficiency:

$$\eta = 1 - \frac{T_L}{T_H}$$

T_L: heat sink temperature, T_H: receiver temperature

- Typical engines reach up to 50-70% of Carnot efficiency due to unavoidable heat losses

CSP system

Wet/dry cooling

- CSP plants (parabolic trough, linear Fresnel, power tower) use Rankine cycle
- Pressurized water is boiled, steam drives engine to generate electricity
- Steam is then condensed and water re-pressurized. Use of external cooling water and evaporative cooling tower
- Wet cooling most common, efficient, lowest cost
- It can consume more water than fossil fuel plants

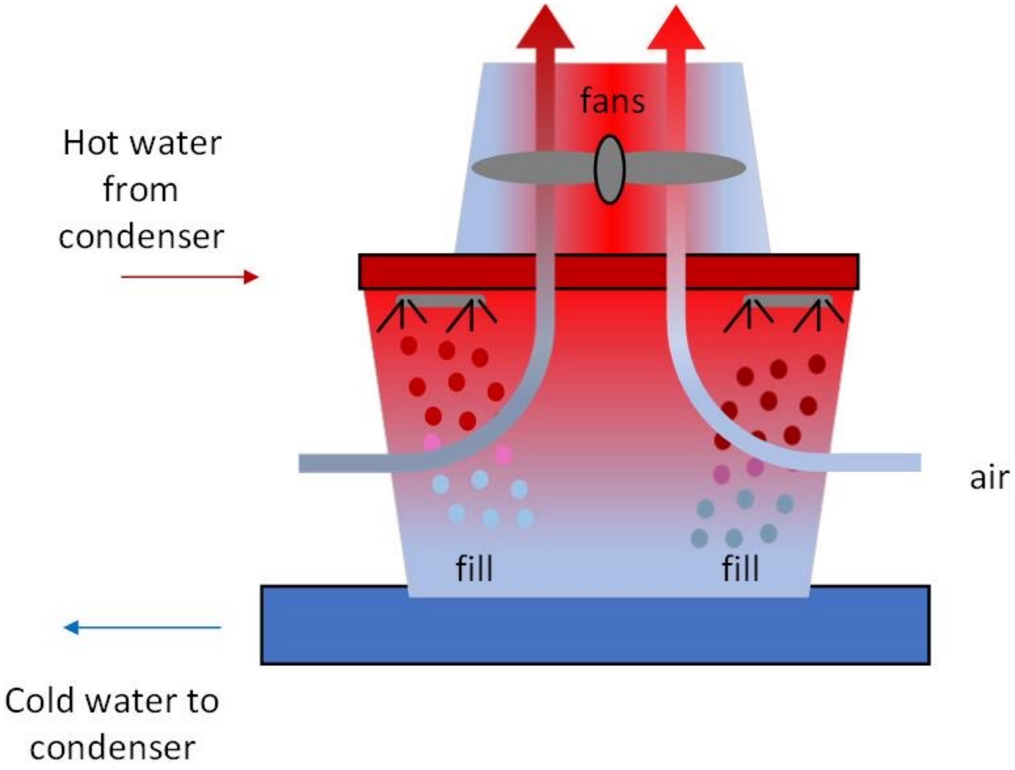

Figure 6-28: Wet cooling system.

CSP system

Wet/dry cooling

- Dry cooling can eliminate 90% of water requirement
- Heat from condenser is rejected by means of fans and ambient air
- Should be large temperature difference between outside air and exhaust steam, method doesn't work well on hot days
- Higher costs, lower CSP system performance
- Hybrid wet-dry cooling doesn't affect performance so much and decreases water consumption

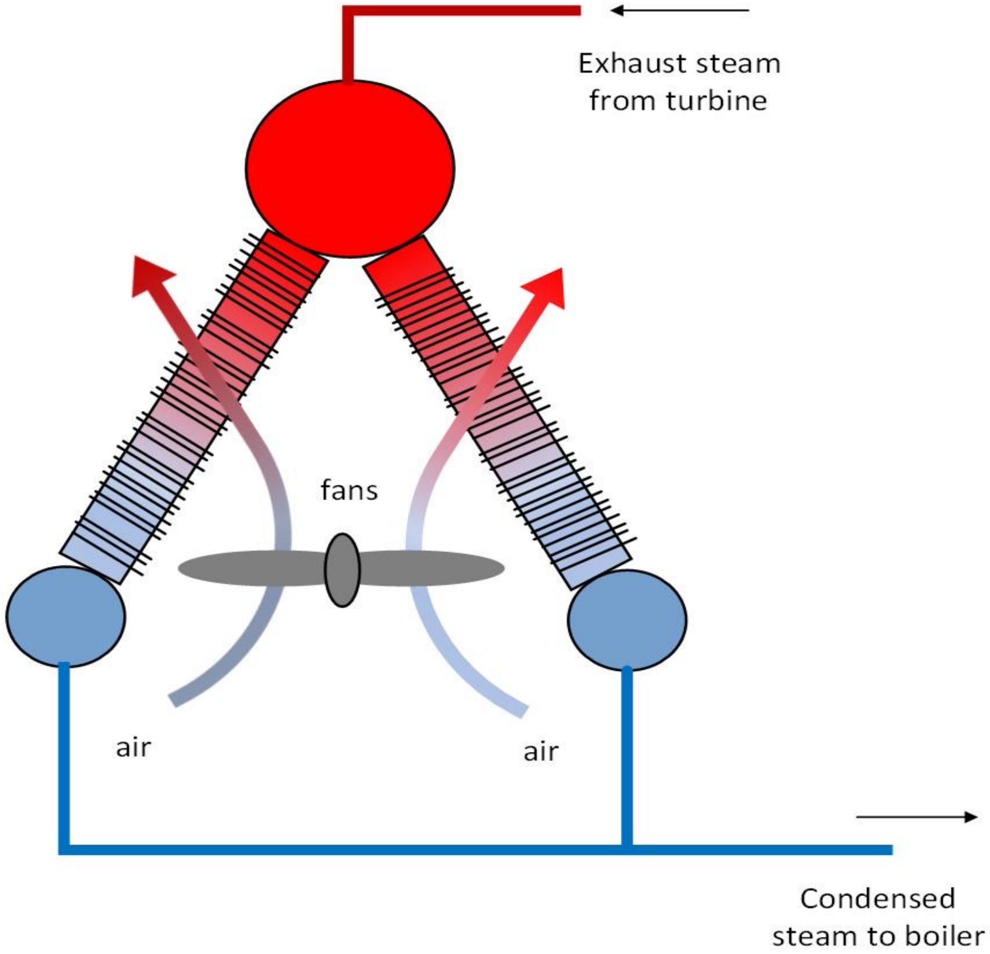

Figure 6-29: Dry cooling system.

Hybridization

- CSP technologies exploit the thermal capacity of solar energy to drive a power cycle, like a steam Rankine cycle
- They are a promising source that can be integrated into established power systems
- TES systems increase CSP reliability and are cheaper than the batteries that PV systems incorporate
- Hybridization further increases CSP reliability, as CSP technologies are coupled with other energy sources to produce power

Hybridization

PV-CSP hybrid system

- PV systems directly convert solar energy into electricity via solar cells
- Only photons with energies near the cell material band gap are converted to power
- Majority of irradiance is converted to heat
- PV also present issues in large scale electric energy storage
- CSP and PV technologies can be complementary to each other forming a PV-CSP hybrid system

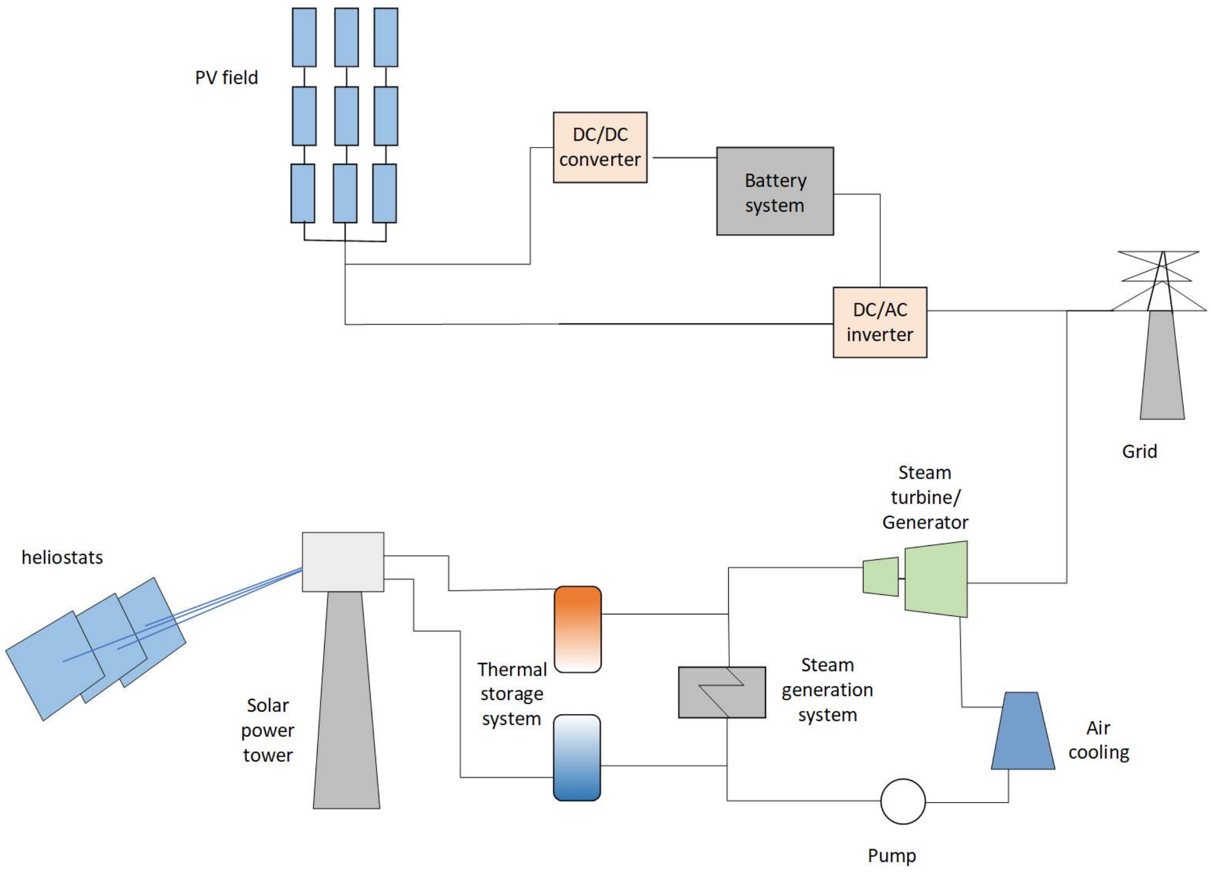

Figure 6-30: Design of a hybrid PV-CSP plant with energy storage.

Hybridization

PV-CSP hybrid system

- Solar energy is fully exploited, increasing system efficiency and reducing costs
- PV-CSP system can be: non-compact, including flat PV-CSP and CPV-CSP system and compact, including PV-topping and spectral beam splitting (SBS) technology
- *Non-compact hybrid system:* PV and CSP operate independently
- System is integrated together by the electric dissipating or control system
- PV is responsible for part of the station-service power for the CSP
- This type of hybrid can provide stable power output and have high capacity factor, >80%

Hybridization

PV-CSP hybrid system

- *Compact hybrid system:* takes advantage of different methods for energy conversion in PV and CSP
- Photons with lower energies than the band gap of cells are transmitted and converted to heat in the cells substrate
- Photons with higher energies, are partly converted to electricity in PV process and rest is used as heat
- Compact PV-topping hybrid system: dissipated heat of PV cells is used for power production via CSP system, cells are used as thermal receiver and PV converter at the same time. PV is topping cycle, CSP bottoming cycle

Hybridization

PV-CSP hybrid system

- SBS hybrid system: spectral beam of solar radiation is split, visible light can be converted to electricity in PV cells and near-infrared/ultra-violet light is converted to heat in CSP system
- Higher conversion efficiency is achieved for solar cells and temperature of CSP's working fluid is not limited by them
- PV-topping and SBS technologies can be combined to achieve lower PV temperatures and higher working fluid temperatures

Hybridization

CSP-fossil fuel hybrid system

- CSP technologies can be coupled with fossil fuels that can dispatch energy in times of unavailability of solar energy
- A power plant can this way have consistent operation, improved capacity, increased efficiency
- Most common is integration of solar collectors with the steam cycle of a combined cycle gas turbine (CCGT) plant or coal plant
- In a CCGT plant, after completion of first engine’s cycle, working fluid (exhaust) has high enough temperature to be used in second heat engine
- Depending on type of solar collector and fossil fuel plant, integration is achieved in various ways

Hybridization

CSP-fossil fuel hybrid system

- Parabolic troughs that can operate at around 400 °C, can be used to evaporate steam in Rankine cycle or a CCGT plant
- Linear Fresnel reflectors that usually operate below 300 °C, can use concentrated heat to replace the auxiliary steam in feed water preheating in coal plants
- Process of retrofitting fossil fuel plant with solar collectors depends on plant age, land availability, solar resource of location
- Hybridization of CSP and fossil fuel systems can increase power capacity, decrease costs and reduce the effect of fossil fuels on environment

- In this chapter, concentrated solar power technologies were presented along with types of thermal energy storage. Solar water heating methods were described and various issues of a CSP system were discussed.

Summary

Solar thermal systems

Thank You

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

Section Outline

In this section, examples of photovoltaic applications are given. The economics of PV systems and their environmental aspects are discussed. The effects on PV performance are presented. The types of tracking systems are described.

Section 1

Photovoltaic system calculation and aspects

This week’s topics…

- Photovoltaic applications
- Economics of PV systems
- Environmental aspects
- Effects on PV performance
- Tracking systems

PV applications

Solar home systems

- Solar home systems (SHS) power off-grid houses, common in developing countries
- Usual operation at 12 V DC voltage
- Power appliances, like radios, TVs, lights etc. for a few hours a day
- Can power AC loads with the use of inverter
- Consist of one or more PV modules, one or more batteries, charge controller, inverter
- Size determined by engineers

Figure 5-1: Solar home system in a house in Peru.

PV applications

Solar home systems

- PV panels on roofs or poles and tilted
- Batteries should be close to panel in cool, dry location
- Low supervision and maintenance
- High initial cost, battery the most expensive component
- Possibility of funding, monthly payments or microleasing
- Replace kerosene, candles. Reduce indoor air pollution

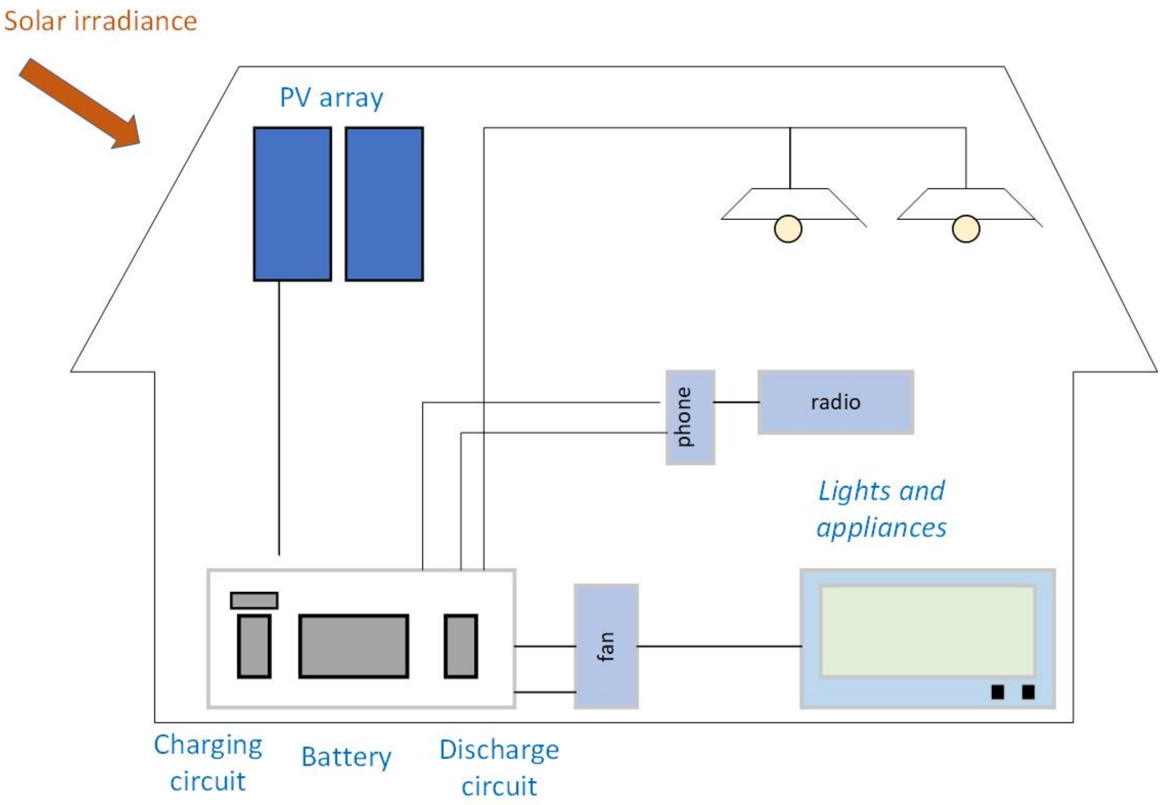

Figure 5-2: Schematic of a typical DC solar home system.

PV applications

Solar home systems

System sizing

- Calculation of load: few light bulbs, TV, radio, phone charger, 4-5 hours a day would require around 200 Wh/day
- Calculation of peak sun hours (PSH) (days with average solar irradiance 1000 W/m^2): consider PSG=5 for worst month
- 200 Wh/day = PV output*PSH*performance ratio
- If ratio=55%, PV output=72.7W so a PV module of 75W should be selected

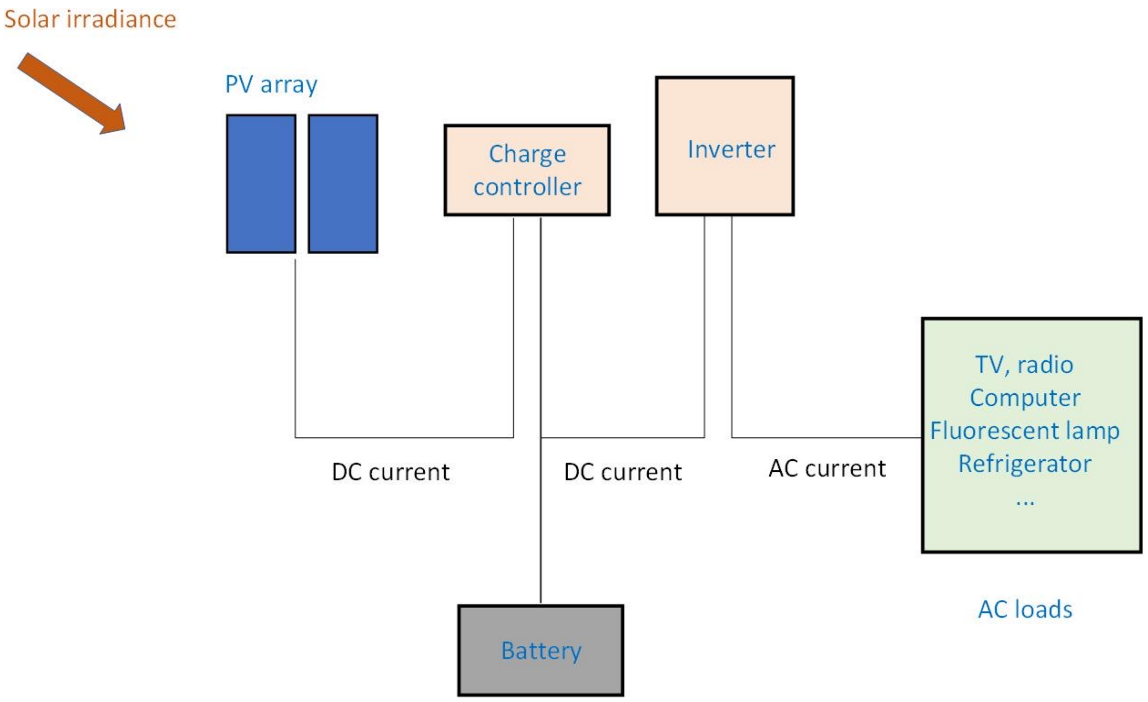

Figure 5-3: Solar home system with AC loads.

PV applications

Solar home systems

- Selection of battery: stored energy = (desired number of days of autonomy*energy load per day) / battery depth of discharge (DOD)
- If days of autonomy=4, energy load/day=200Wh, DOD=70% then stored energy=1142.8Wh
- Stored energy=battery capacity(Ah)*battery terminal voltage
- If voltage=12V, capacity=95.2Ah, so a 12V, 100 Ah battery should be selected
- Solar home systems installed in many countries, like Peru, Bangladesh for life quality improvement

PV applications

PV water-pumping system

- PV water-pumping system in off-grid areas
- Consists of PV panel, pumps, may include batteries for energy storage, charge controlle
- DC current from PV panels either supplied to pump or stored in batteries for later use
- PV electricity drives a usually submersible motor pump, pumps water to elevated water tank
- Due to gravity, water flows from tank to water taps for public, places for feeding livestock or irrigation system

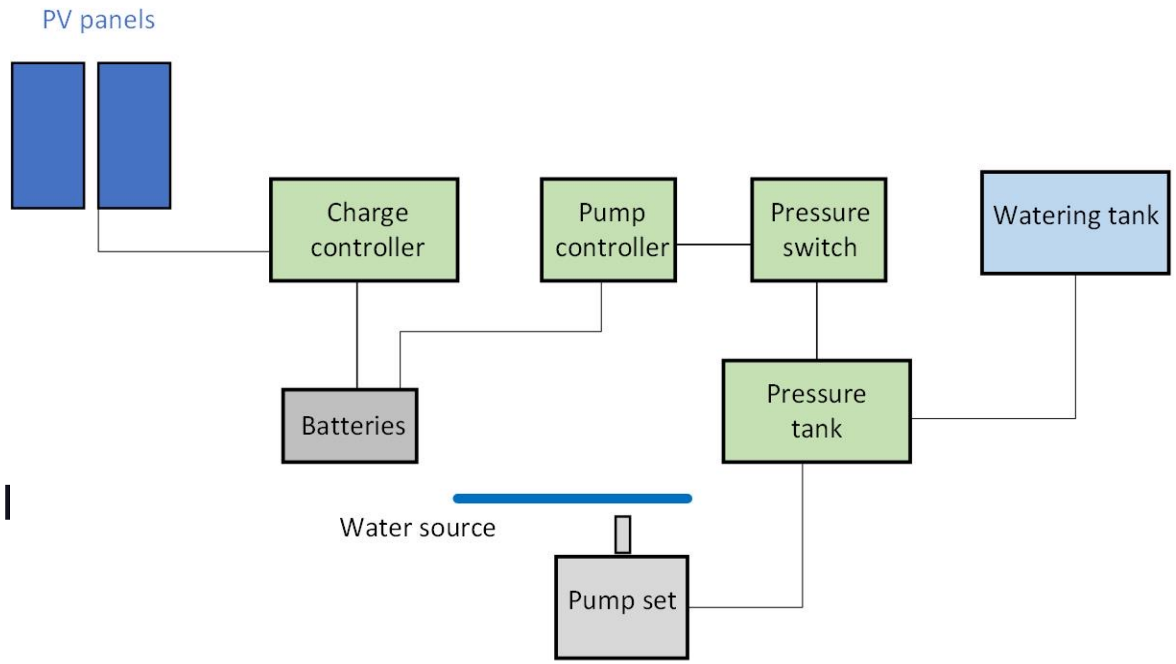

Figure 5-4: Schematic of a PV-powered water-pumping system.

- Solar water pumps use DC current as opposed to AC conventional pumps

PV applications

PV water-pumping system

- System with batteries: batteries charged during the day, power pump to extend operation period. Steady voltage to pump motor
- Batteries reduce system’s efficiency because supplied voltage can be lower than PV produced voltage. Pump controller is used to boost battery voltage before supplied to pump
- System without batteries: electricity sent directly from PV panel to pump, which operates only during day
- Pumped water depends on sunlight received, changes during day, so good match is required between panel and pump for efficient operation
- Designed to store more water during day for later use, larger tanks

PV applications

PV water-pumping system

System design

- Determination of water supply needs, domestic water and irrigation water
- Calculation of pumping head = elevation head (distance between water source surface level and outlet pipe level) + major losses head (depend on rate of water flow, pipe type and dimensions) + minor losses head (depend on pipe components e.g. valve, elbow)
- Solar resource estimation
- Selection of solar pump: must meet daily water flow and pumping head requirements

PV applications

PV water-pumping system

- Three pump types: centrifugal pump similar to conventional pump, helical rotor pump with one turning part, piston (diaphragm) pump with more moving parts
- Choose pump head specification higher than required pumping head
- Selection of PV panel: size depends on pumping head, require water amount, solar resource available
- PV water-pumping system has no costs for fuel, long lifetime
- Unattended operation, low maintenance
- High initial cost, no battery system is less expensive

PV applications

PV refrigeration system

- PV refrigeration systems used off-grid to keep food, medicine, vaccines
- Thick insulation, use DC vapour compression cooling systems
- May use batteries for energy storage, but are more expensive and batteries deteriorate in hot temperatures
- NASA Johnson Space Center designed solar-powered refrigeration system without batteries, uses phase change material to store thermal energy for later use

Figure 5-5: PV-powered refrigeration system.

PV applications

PV refrigeration system

- DC power from PV panel used to drive compressor, refrigerant is circulated through a vapour refrigeration loop, which extracts heat from an insulated enclosure
- In the enclosure there are the thermal reservoir and phase change material, which freezes when there's heat extraction from enclosure
- Temperature maintained inside enclosure when sunlight not available
- Variable speed DC compressor to operate longer during day and take advantage of variations in solar resource

PV applications

PV refrigeration system

- Speed of compressor is controlled by a microprocessor, to maximize speed for available solar power
- PV panel kept at peak power point during compressor operation
- Microprocessor does load testing of panel before turning on compressor, cabinet temperature control, compressor speed control
- Capacitors incorporated into system to smooth power voltage so additional current is provided during start-up of compressor

PV economics

- PV prices have reduced with time due to technology improvements, manufacturing processes, installation costs, distribution channels etc.
- Policies implemented to support PV energy production
- Financial incentives make the PV industry competitive
- PV technology cost declined at 82% mainly due to reduction in module prices and balance-of-system costs

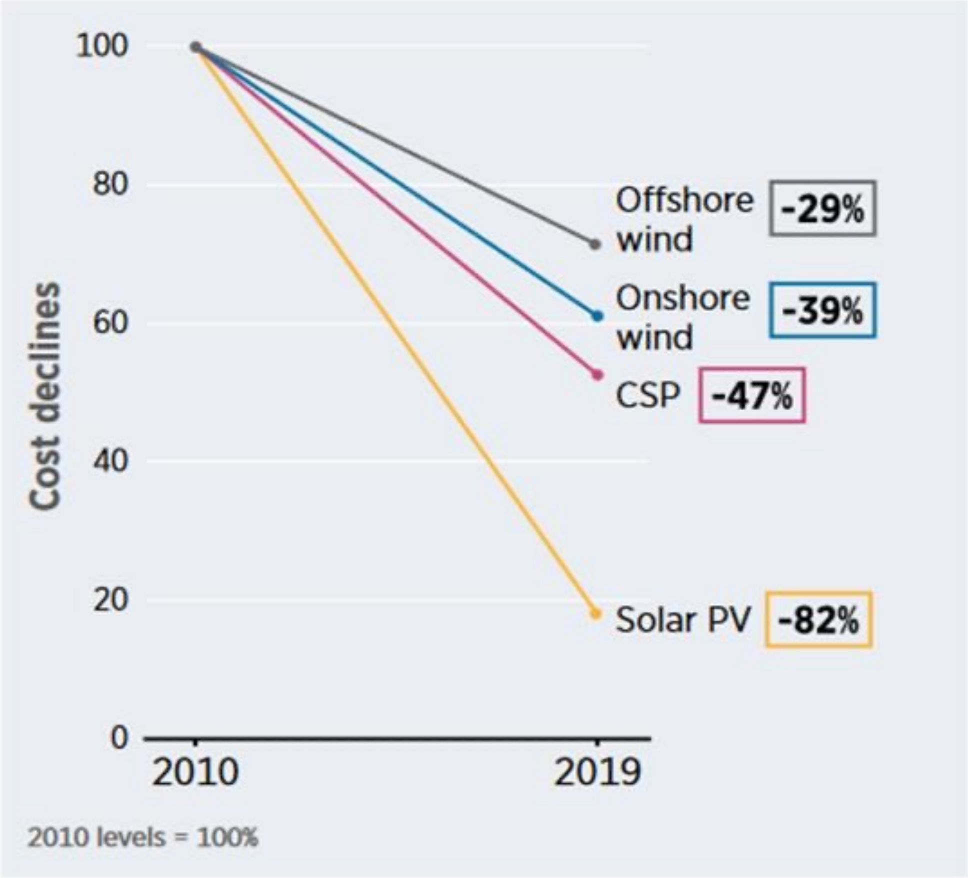

Figure 5-6: Cost decline in renewable energy technologies from 2010 to 2019.

PV economics

Payback time

- Payback time (financial) is defined as the time is takes to recover the investment cost

$$\textit{payback time} = \frac{\textit{initial investment}}{\textit{annual return}}$$

- Depends on annual solar radiation received by PV system, location, orientation
- Payback time decreases with utility costs increase
- Other factors that influence payback time are initial costs, variations in value of money due to inflation, policies that are implemented

PV economics

Financial compensation

- Compensation for PV owners who feed power into utility grid, like net metering and feed-in tariffs
- When excess power is fed into grid, electricity meters measure both electricity consumed from grid and the one delivered into grid. User pays only net electricity consumption
- Feed-in tariffs: PV electricity sold to utility company at fixed price.

PV economics

Financial compensation

- Gross feed-in tariffs: all generated electricity sold to grid and all consumed electricity bought from grid
- Net feed-in tariffs: electricity consumption subtracted from electricity generation, only excess amount is sold
- Installation of PV is encouraged when feed-in tariffs higher than electricity price, otherwise self consumption is encouraged

PV economics

Self consumption

- Self consumption: user uses generated electricity for own electrical needs

- Generated PV energy consumed instantaneously

- PV generated electricity has variations, peaks difficult to predict by utility companies, electricity fed into grid may be higher than the grid needs, so self consumption is encouraged

PV economics

Self consumption

- To achieve self consumption, size of PV system is reduced so peak power always lower than peak power consumed by user
- Better option is to include storage devices
- Net metering doesn't promote self consumption, generated and consumed electricity are treated the same. Feed-in tariffs promote self consumption when they are lower than retail energy

PV economics

Levelized cost of electricity

- Levelized cost of electricity (LCoE) defines the electricity cost, per kWh, produced from a power generation facility
- Used to compare lifetime costs of different electricity production technologies
- Ratio of all costs during facility's lifetime to all energy produced over lifetime

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t, M_t, F_t, E_t: investment expenditures, operations and maintenance expenditures, fuel expenditures, electrical energy, generated in year t

n, r: expected lifetime of facility and discount rate

PV economics

Levelized cost of electricity

- Discount rate used to discount future costs so they can be translated in present value
- For PV systems, F_t is zero
- LCoE for a PV system varies between different countries
- LCoE is good indicator of the competitiveness of an energy technology
- Profit is made when LCoE is lower than electricity price

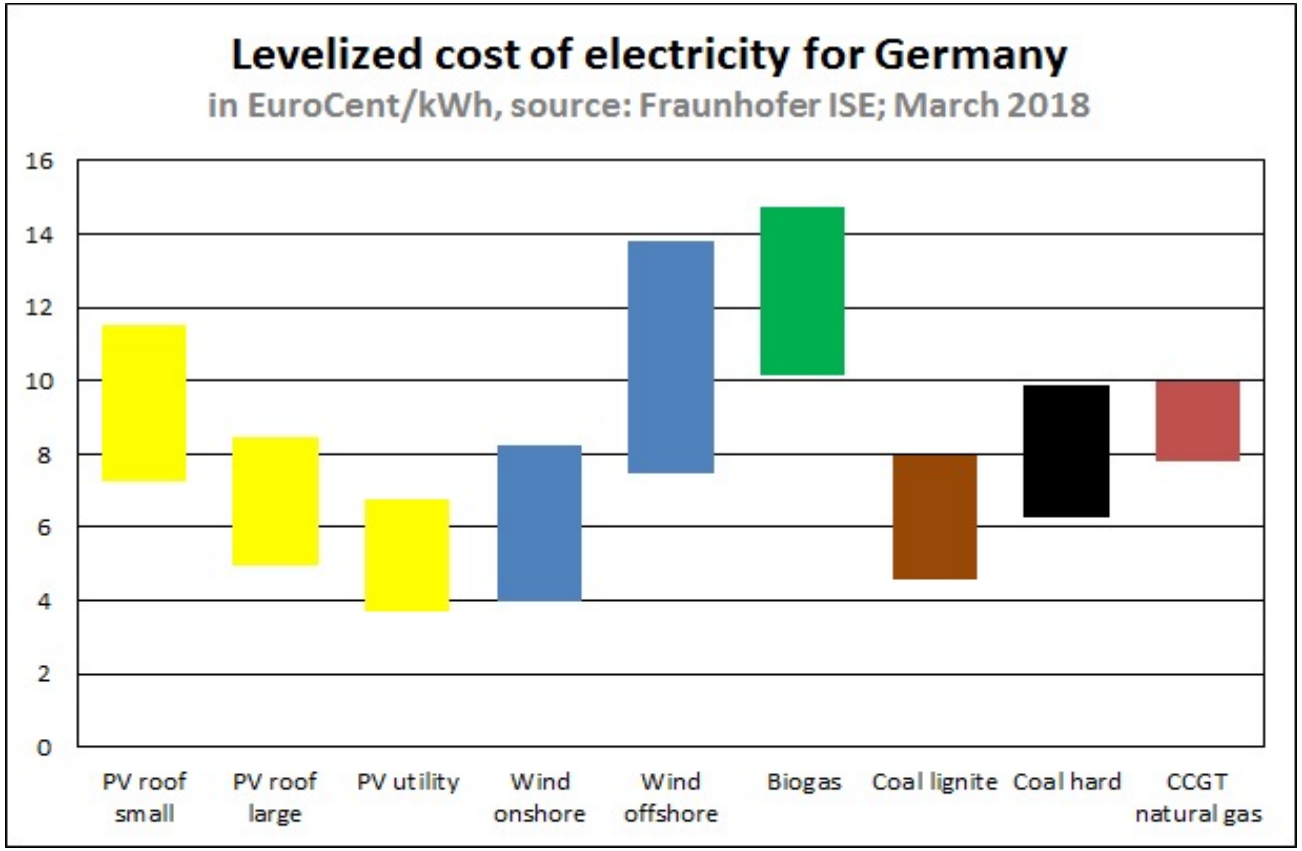

Figure 5-7: LCoE per energy technology, for Germany 2018.

PV economics

Grid and socket parity

- Grid parity is the point when the LCoE of PV electricity is equal to that of other electricity production technologies, without considering subsidies and incentives
- Socket parity is the point when LCoE of a PV system is equal to the price paid by the consumer for grid electricity
- Grid parity will occur when the PV power producer will sell electricity to utility company at the same price the company is paying other power generators
- Socket parity will occur when PV power is the same price as electricity that a consumer buys from utility company
- When the technology is close enough to grid parity, it can be included in the electricity mix

PV economics

Life-cycle cost

- There are various costs in a PV system: installation costs, operating and maintenance, replacement, decommissioning costs
- Life-cycle costing calculates all costs of PV system throughout its lifetime, taking into account the time value of money
- May take into account incentives, loan costs etc.
- The value of money over time is affected by the inflation rate and the discount rate
- Inflation rate, i, describes the decline in value of money with time. e.g. if inflation rate is 2% per year, the same item will be 2% more expensive the next year, the value of money is decreased

PV economics

Life-cycle cost

- Discount rate, d, describes the interest earned on saved principal. Invested money can be increased due to positive interest rate
- If N_0 is invested at a rate of d% per year, after n years the increased amount N(n) will be:

$$N(n) = N_0(1+d)^n$$

- If an investment is made at the cost of C_0 and the inflation rate is i%, then after n years the cost of the same investment will be:

$$C(n) = C_0(1+i)^n$$

- Inflation and discount rate fluctuate with time

PV economics

Life-cycle cost

- If C_0=N_0, then the ratio of C(n) to N(n) is the dimensionless quantity Pr, which describes the present worth factor of an item which will be bought in n years time.

$$Pr = \left(\frac{1+i}{1+d}\right)^n$$

- The present worth, PW, of an item, is the amount of money that should be invested in the present at a d% rate so the item can be bought in n years, assuming an inflation i%

$$PW = (Pr)C_0$$

- Life-cycle cost (LLC) of a PV system is calculated as the sum of PWs of individual system costs

Environmental aspects

- Carbon footprint is used to estimate CO2 emissions due to PV panels manufacturing and compares these emissions with the CO2 reduction due to the use of the PV system instead of fossil fuels
- Another approach is to study the total energy required to manufacture the PV system with all its components
- Life-cycle analysis (LCA) is a method of assessing the environmental impacts during a project’s lifetime
- Energy yield ratio is used to address the ecological aspects of PV systems and is the ratio of total energy yield of a PV system in its lifetime to total amount of energy invested in the system for that time

Environmental aspects

- Energy payback time is the ratio of total energy investment required over project's lifetime to the average annual energy yield of the project

$$energy\,payback\ time = \frac{total\ invested\ energy}{average\ annual\ energy\,yield}$$

- PV systems usually have an energy payback time 1-7 years
- Thin film modules from a-Si, CdTe or CIGS requires less energy than crystalline silicon modules
- Technology improvements reduce the amount of energy required for PV module production

Environmental aspects

- Energy payback time differs between system parts, like module, module frame, balance of system
- Rooftop installations have lower energy payback times, because balance of system for ground mounted systems is more energy extensive
- Energy payback time is lower than the lifetime of systems, which is around 25-30 years
- Another environmental impact of PV is pollution from their production, due to toxic chemicals that may be involved

Environmental aspects

Other aspects of PV

- Land use for PV systems installation is smaller than the one required for conventional energy resources
- Land may be unavailable due to other uses, e.g. agriculture
- PV take advantage of already made structures, roofs, façades of buildings
- May have negative visual effects
- PV can be used to power off-grid areas, e.g. In developing countries
- Energy storage is needed for continuous supply
- Reduction of dependency on oil and imports
- Job openings, increase in development and education levels, environmental consciousness

Effects on PV performance

Solar irradiance

- ○ Solar irradiance affects the PV system power output
- ○ Increase in irradiance brings an increase in output power
- ○ PV systems are more effective in locations with good solar resource

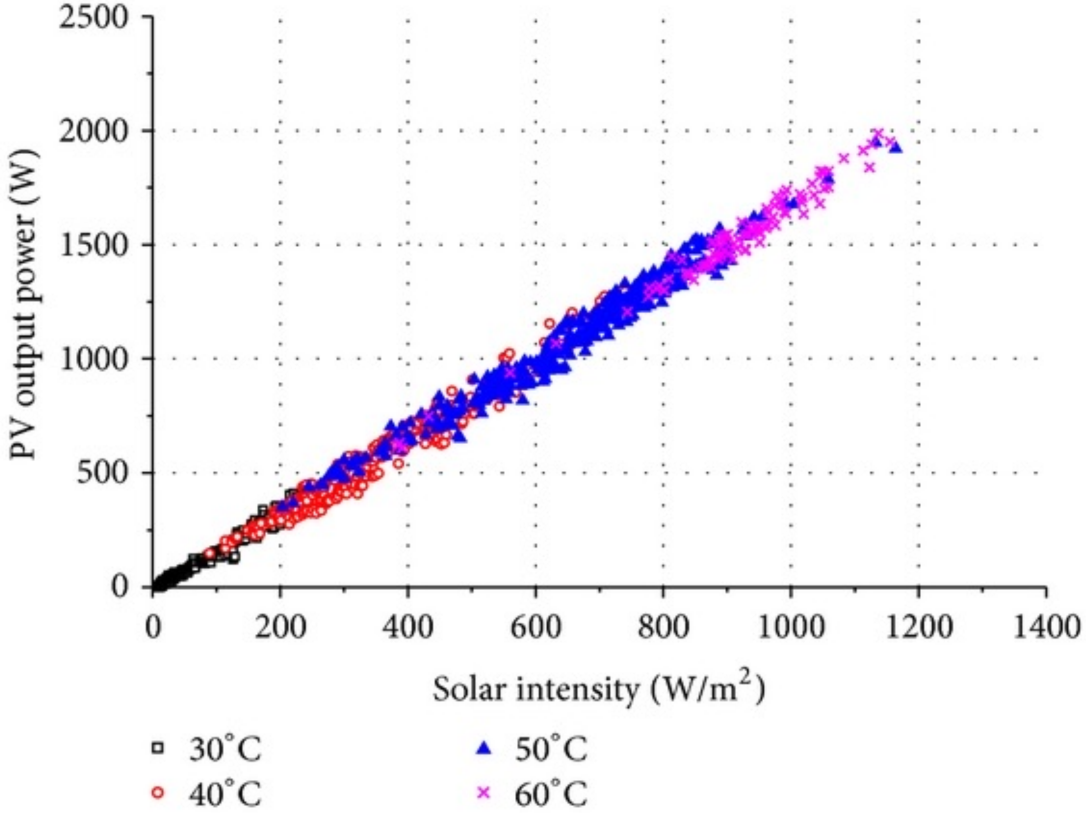

Figure 5-8: Power of PV module as a function of irradiation.

Effects on PV performance

Temperature

- PV cell is a semiconductor, sensitive to temperature variations
- Increase in temperature results in reduction in power output
- Normalized maximum power and open circuit voltage show a linear decrease with temperature
- Normalized short circuit current presents slight increase with temperature
- Reduction in voltage is much higher than the increase in current, resulting in reduction in power output

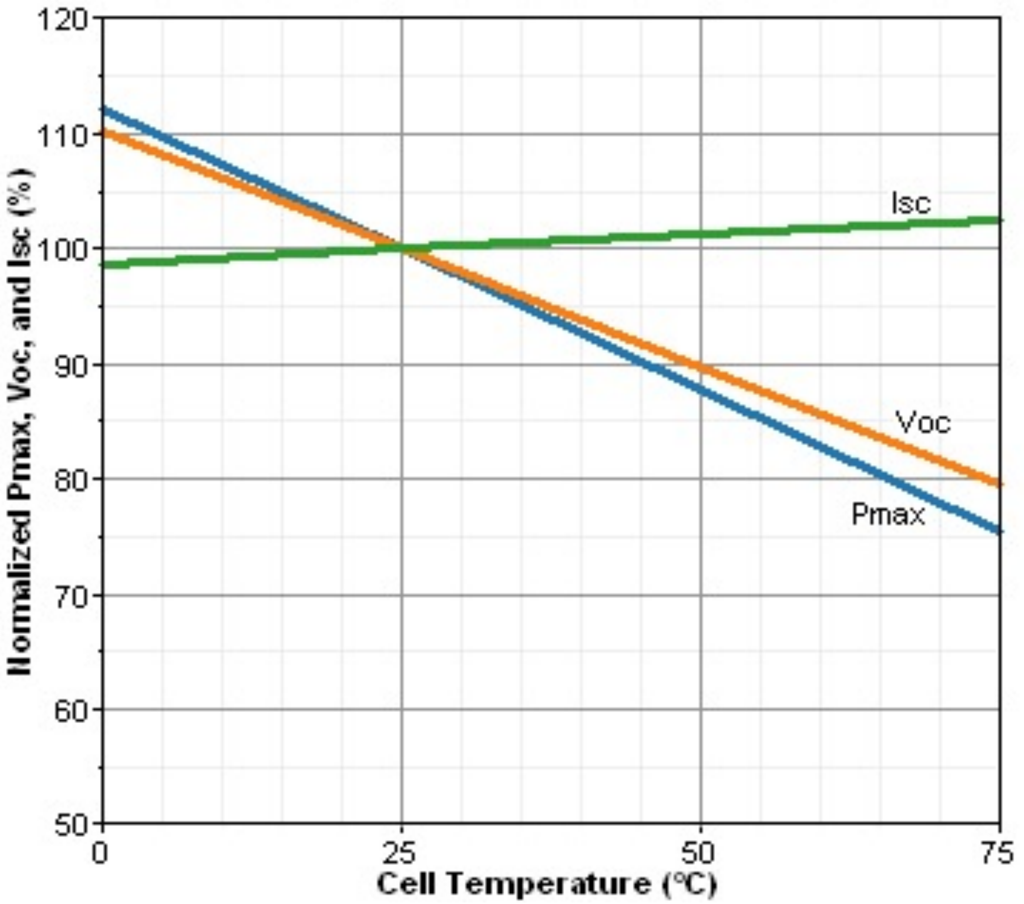

Figure 5-9: Normalized P_{max}, I_{SC} and V_{OC} as a function of temperature.

Effects on PV performance

Temperature

- Cell's efficiency decreases with temperature, mainly because of the increase in the rate of internal carrier recombination due to increased carrier concentration
- PV module temperature increases with solar radiation increase and air temperature increase but decreases with wind speed
- PV system can be protected with air circulation between module and roof/ground, using light coloured panels, cooling fans

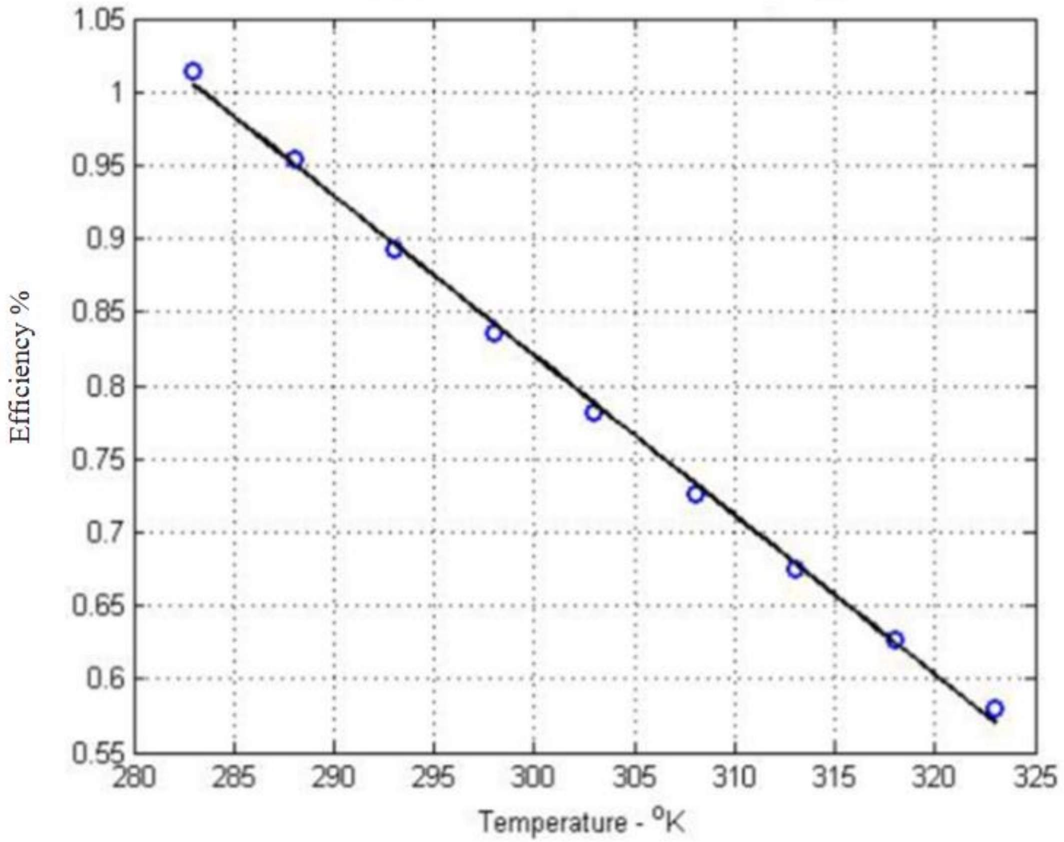

Figure 5-10: Conversion efficiency of a silicon cell as a function of temperature.

Effects on PV performance

Shading

- PV system output is sensitive to shading, which can occur because of clouds, trees, buildings, dirt etc.
- Shading causes mismatches in the current generated from individual solar cells of the module
- Partial shading of even a single cell can lead to reduction of power output
- A shaded cell generates less current
- Cells connected in series must have same current flowing through them
- If current is higher than the shaded cell's capability, the cell will be overheated and possibly damaged
- If current is less than the shaded cell's capability, the overall current and power of the string will be limited

Effects on PV performance

Shading

- Bypass diodes are used to limit shading effects
- Bypass diode is connected in parallel to a sub-string of the module
- Common PV modules with 60 or 72 cells have 3 bypass diodes
- Diode acts as an open switch under no shading and light received by each cell is uniform
- Under shading, the diode connected to that sub-string acts as a closed switch and bypasses that sub-string

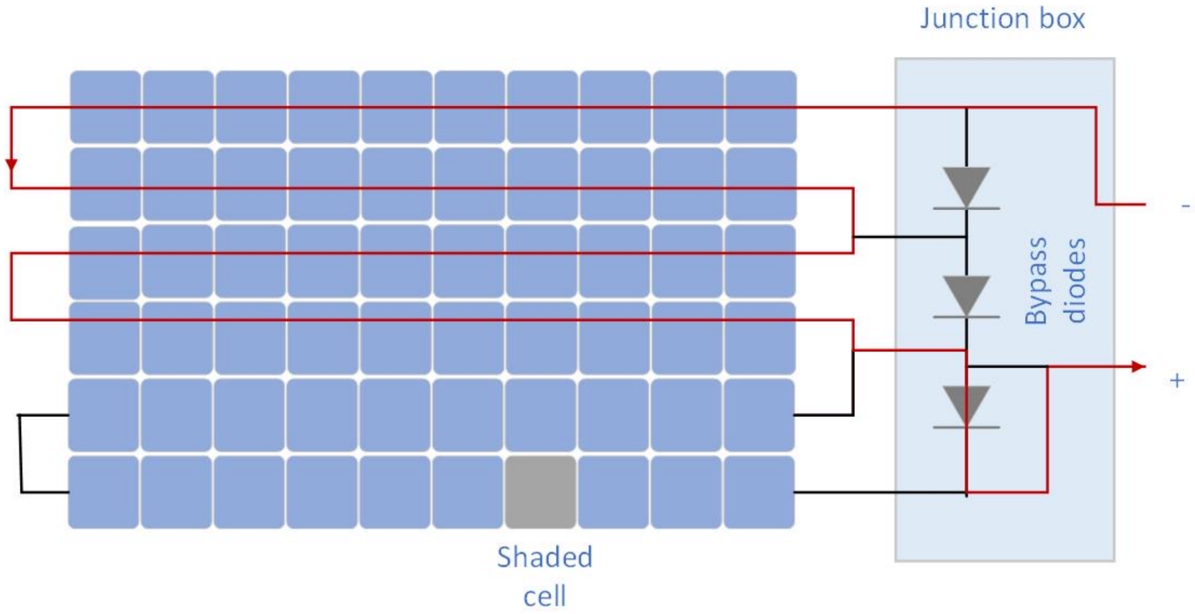

Figure 5-11: PV module with bypass diodes.

Effects on PV performance

Shading

- I-V and P-V curves of PV system change due to partial shading
- With no bypass diodes, the shaded cells will operate with a reverse bias voltage to provide same current, causing a reverse power polarity which leads to power consumption and maximum generated power reduction
- With bypass diodes, there's an alternate current path, so cells don't carry the same current anymore
- P-V graph will present multiple maxima

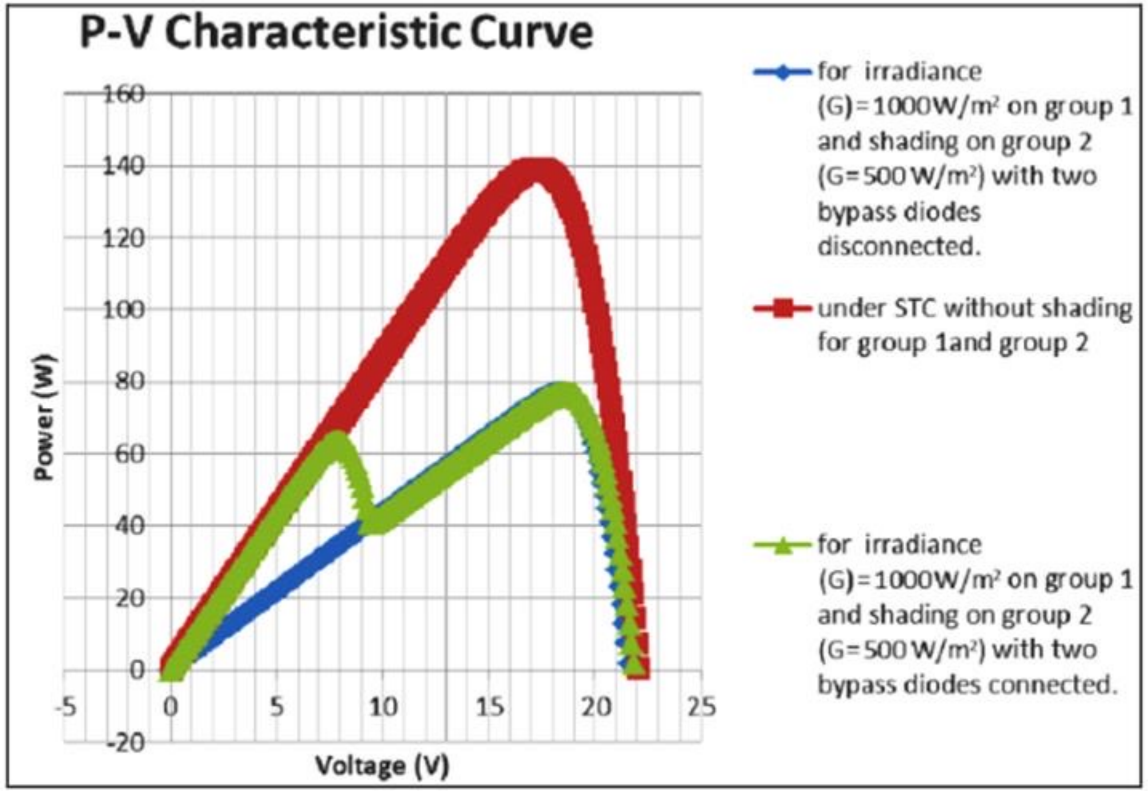

Figure 5-12: P-V curve of a PV module under various conditions.

Effects on PV performance

Shading

- Usual MPPT algorithms can't distinguish between a local and a global maxima
- In string inverters, the MPPT controller is at the string level and responds to the least efficient module of the string, therefore several modules will operate below their MPP
- MPPT algorithm must consider entire range of string voltage to detect global maxima. These are the Shade-Tolerant String Inverters
- In micro inverters, each inverter features an MPPT algorithm, mismatches in current between modules won't cause issues

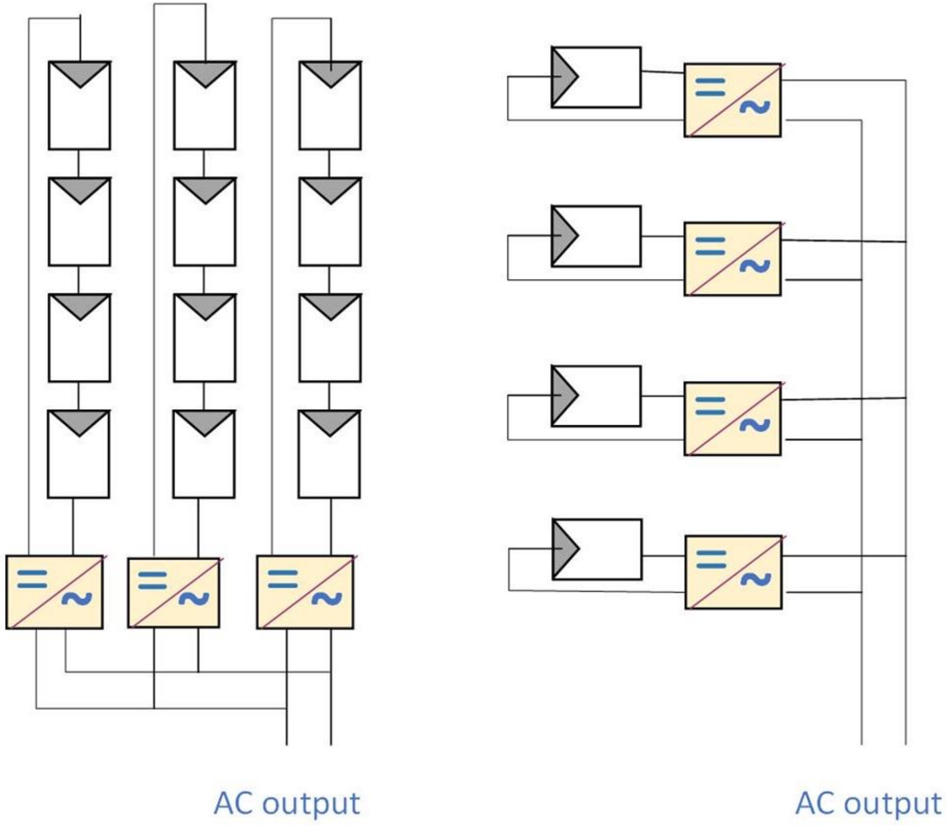

Figure 5-13: Arrangement of string (left) and micro-inverters (right).

Effects on PV performance

Soiling

- Soiling refers to accumulation of dust, dirt, snow and other particles which cover the module surface
- Thin layer is formed on module surface which reduces sunlight received by one or more cells
- Dust particles are minute solid particles with diameters <500μm
- Dust deposition depends on size and weight of particles, weather conditions, tilt angle of module, surface finish of module, wind speed etc.

Effects on PV performance

Soiling

- Location of system is important (coastal, dusty area)
- Horizontal surfaces accumulate more dust than inclined surfaces
- Low wind speeds act in favour of dust settlement
- PV system on a rooftop receives less dust than a ground mounted one
- Soiling can decrease annual power output by 5-17% or more

Effects on PV performance

Soiling

- Dust particles with smaller diameters cause higher losses in performance
- In dust particles of same type, finer particles have greater effect than coarse particles, due to higher ability to decrease the interparticle gap so they’re more effective in blocking the light path
- Soiling effect can be limited with cleaning (self-cleaning glass, electrostatic curtain etc.)

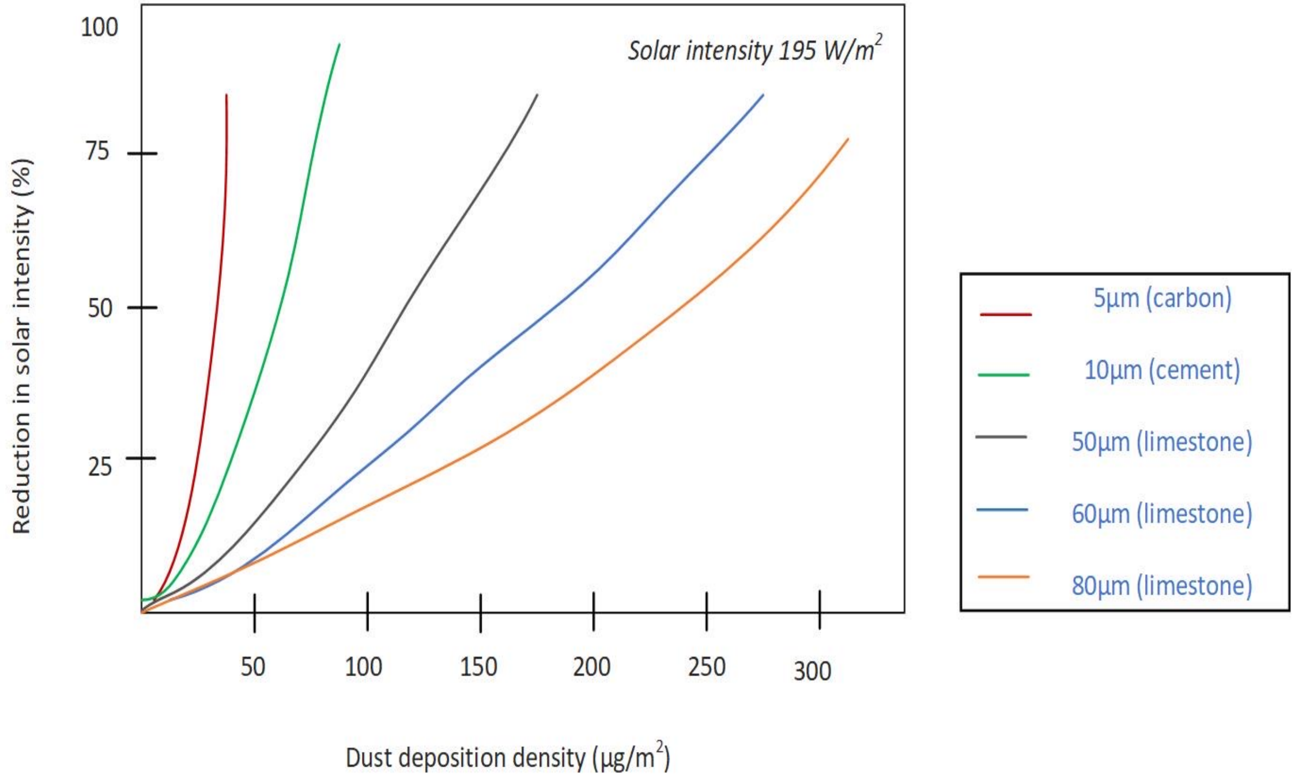

Figure 5-14: Reduction in solar intensity due to dust deposition.

Effects on PV performance

Tilt angle

- ○ Panel orientation is important to achieve maximum output power
- ○ In northern hemisphere, modules are oriented towards true south, otherwise there will be blocking by shade
- ○ For optimum power a module should always face the Sun
- ○ Single-axis trackers can account for daily variations in Sun's position and dual-axis trackers account for daily and seasonal variations

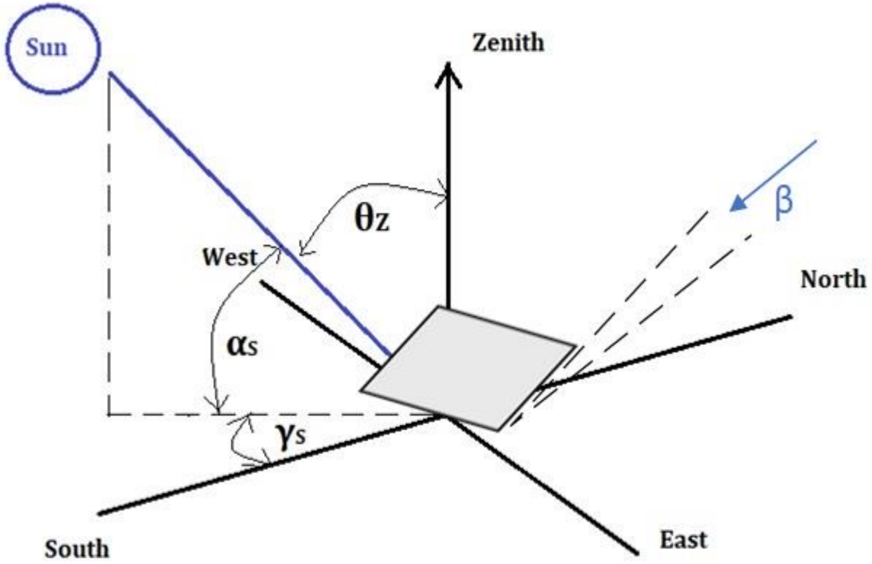

Figure 5-15: The angles of the Sun-panel geometry.

Effects on PV performance

Tilt angle

- Tilt angle is usually fixed at certain inclination
- Optimum tilt angle is usually calculated at $\varphi \pm 15°$, φ the latitude of the location
- "+" is used for winter, "-" for summer
- March and September, tilt angle should be the same as the location's latitude
- Tilt angle adjustment twice or four times a year yields better results

Tracking systems

- Tracking the Sun can increase generated power by 20-25% for a single-axis tracker or 30% and more for a dual-axis tracker
- Tracking enhances PV performance during early morning or late evening
- Effective in locations with good amount of direct sunlight
- Tracking doesn't have important effects in diffuse light conditions

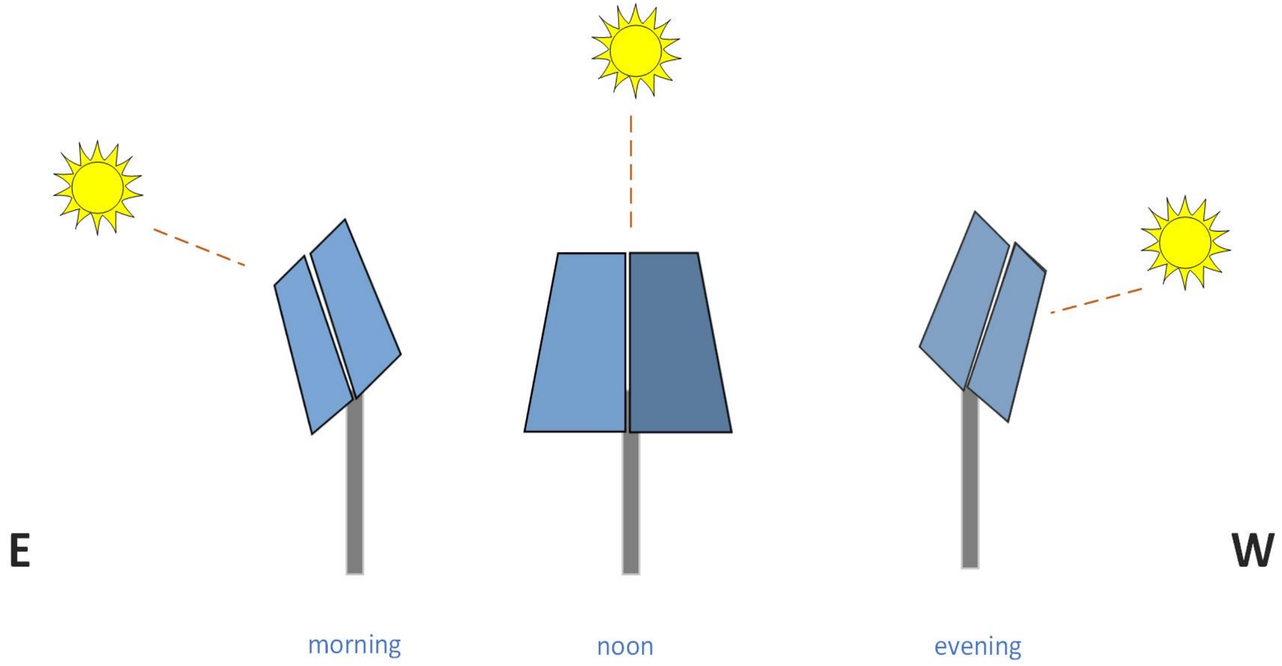

Figure 5-16: A simple design of a solar panel with a tracking system.

Tracking systems

- Classification according to degrees of freedom:
  - single-axis tracking system
  - dual-axis tracking system

- According to control system:
  - Open-loop control system
  - Closed-loop control system
  - Hybrid control system

- According to driving system:
  - Active tracking system
  - Passive tracking system

Tracking systems

Driving system

- In passive tracking systems, the axes move due to pressure difference of special liquids or gases with low boiling point
- Pressure difference in the result of thermal differences created by the shaded and illuminated sides of the tracking system
- When a side is under shade, pressure difference is created and the tracking system moves to eliminate the difference
- Not a lot of precision

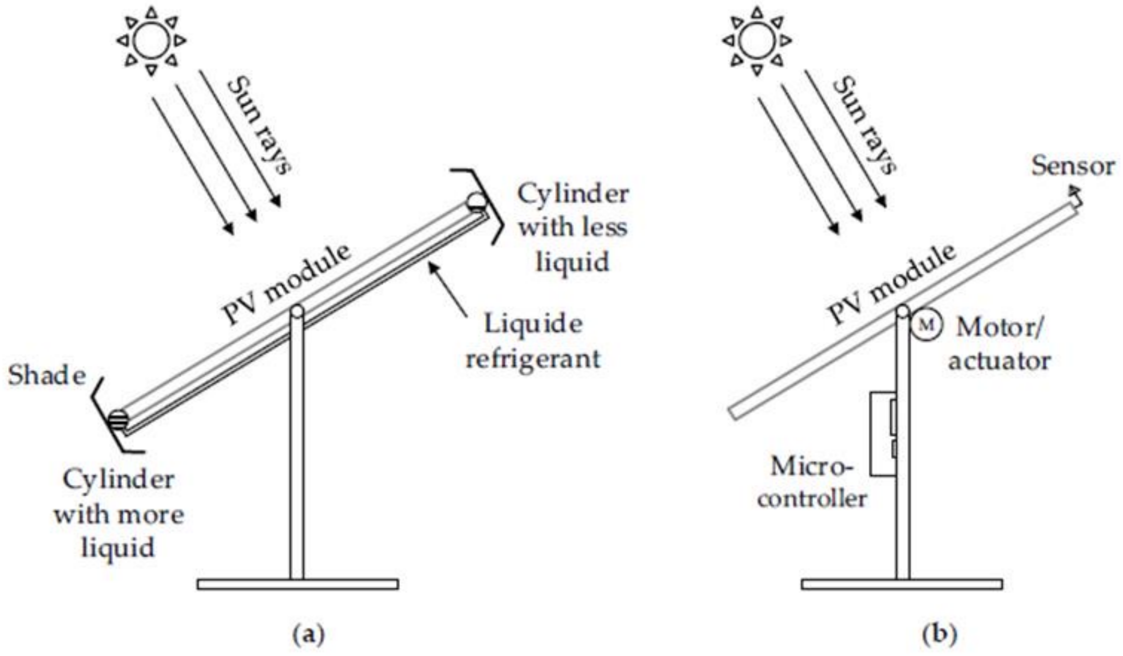

Figure 5-17: Classification based on the driving system: passive (a) and active (b) tracking system.

Tracking systems

Driving system

- Active tracking systems use motors and gear trains for their operation
- Components included are a microprocessor, an electric motor, sensors and gearboxes
- They detect Sun's position and track it
- Based on the control drive, they can be open-loop, closed-loop or hybrid
- Intelligent control: use artificial intelligence or neural network algorithms to control tracking
- Microprocessor control: use Programmable Interface Controllers (PIC) and digital signal microcontrollers
- Sensor-based control systems: use electro-optical sensors and light-dependent resistors (LDR)

Tracking systems

Degrees of freedom

- *Single-axis types:*
- Horizontal single-axis tracker (HSAT), rotating axis is horizontal to the ground, moves in north-south direction
- Vertical single-axis tracker (VSAT), rotating axis is vertical to the ground, rotates from east to west
- Tilted single-axis tracker (TSAT), axis of rotation between horizontal and vertical

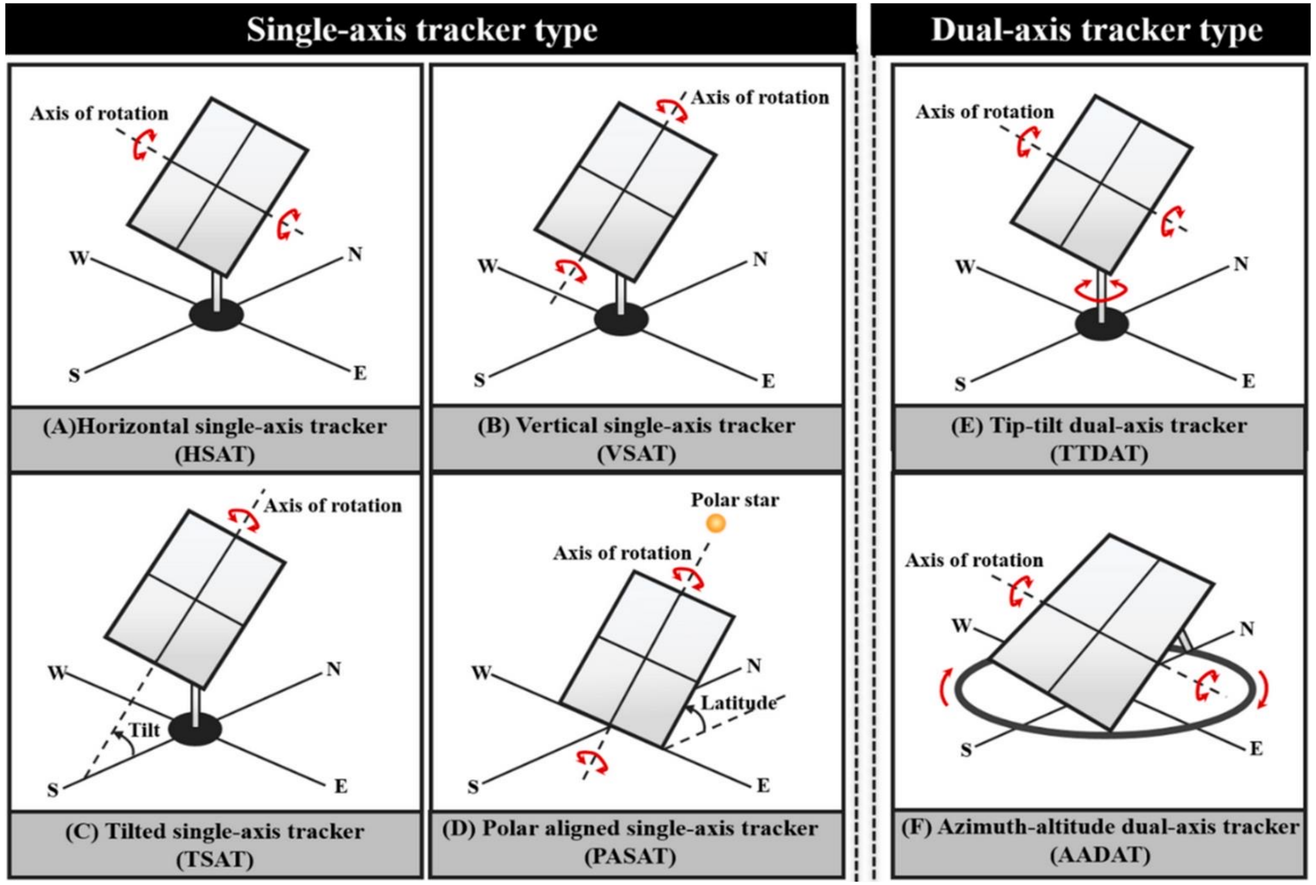

Figure 5-18: Single-axis and dual-axis tracking system types.

Tracking systems

Degrees of freedom

- polar aligned single-axis tracker (PASAT), aligned to polar star. Tilt angle is equal to latitude and rotating axis aligned with Earth’s rotating axis

- *Dual-axis types:*
- Tip-tilt dual-axis tracker (TTDAT), primary axis is horizontal to the ground and secondary axis is normal to primary axis. Tracks in east-west and north-south direction
- Azimuth-altitude dual-axis tracker (AADAT), primary axis is vertical to the ground and secondary axis is normal to primary axis. Tracks east-west, north-south motion of the Sun with the use of a ring mounted on the ground with a series of rollers

Tracking systems

Control system

- Active tracking systems can be classified into: open-loop, closed-loop and hybrid control systems
- Open-loop control system: Sun’s position is determined with a mathematical algorithm, loaded into the microprocessor.
- By controlling input data, like date and time, Sun’s position is calculated from the algorithm for any location

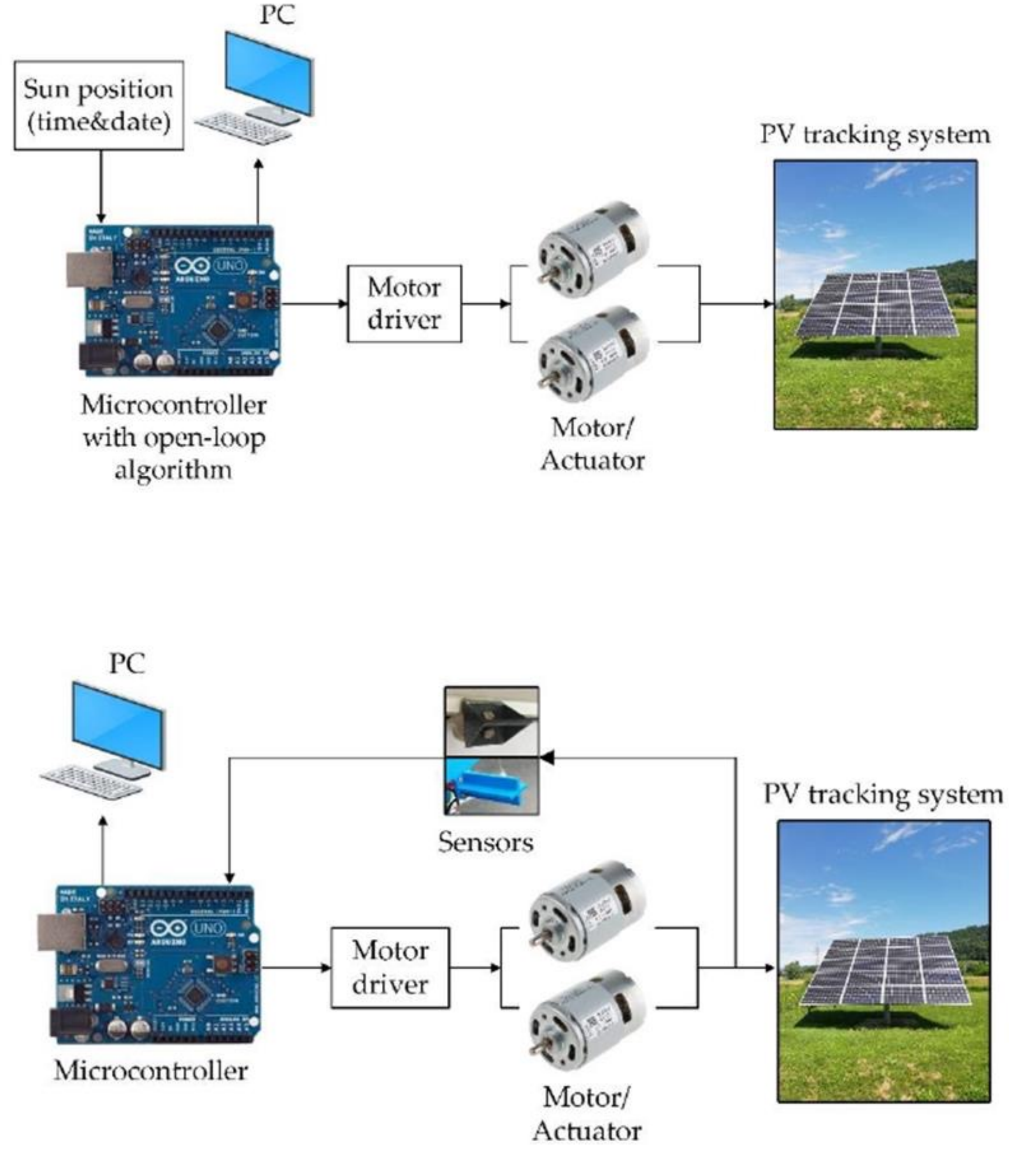

Figure 5-19: Designs of an open-loop (top) and a closed-loop (bottom) tracking system.

Tracking systems

Control system

- Closed-loop control system: use of sensors to find the direction with maximum incident energy, position of the Sun.
- Based on sensors data, the axes move to track the Sun
- Closed-loop control system is based on a feedback control system from the sensors, more expensive, more precise
- Hybrid control system: combines both open-loop and closed-loop systems to take advantage of the benefits of each type
- When adding a tracking system, costs and maintenance should be taken into account along with the increase in power output, as well as the system applicability

- In this chapter, examples of photovoltaic applications were given. The economics of PV systems and their environmental aspects were discussed. The effects on PV performance were presented and the various types of tracking systems were described.

Summary

Photovoltaic system calculation and aspects

Thank You

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Dr Khaled Al Awasa

Introduction to Renewable Energy

Lecture x: Wind Turbines operation and Control

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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This week's topics…

- Background and Introduction
- Wind turbine Classifications
- Wind turbine structure
- Aerodynamics of Wind Turbines
- Examples

Section Outline

In this section, an introduction on wind energy is discussed. The topics that will be covered as follows: Wind Power, Wind Power Origin, Classification of Wind Turbines, Wind Turbine Subsystems, Types of Wind Generation Systems.

Section 7.1

Introduction

Introduction

Wind Power

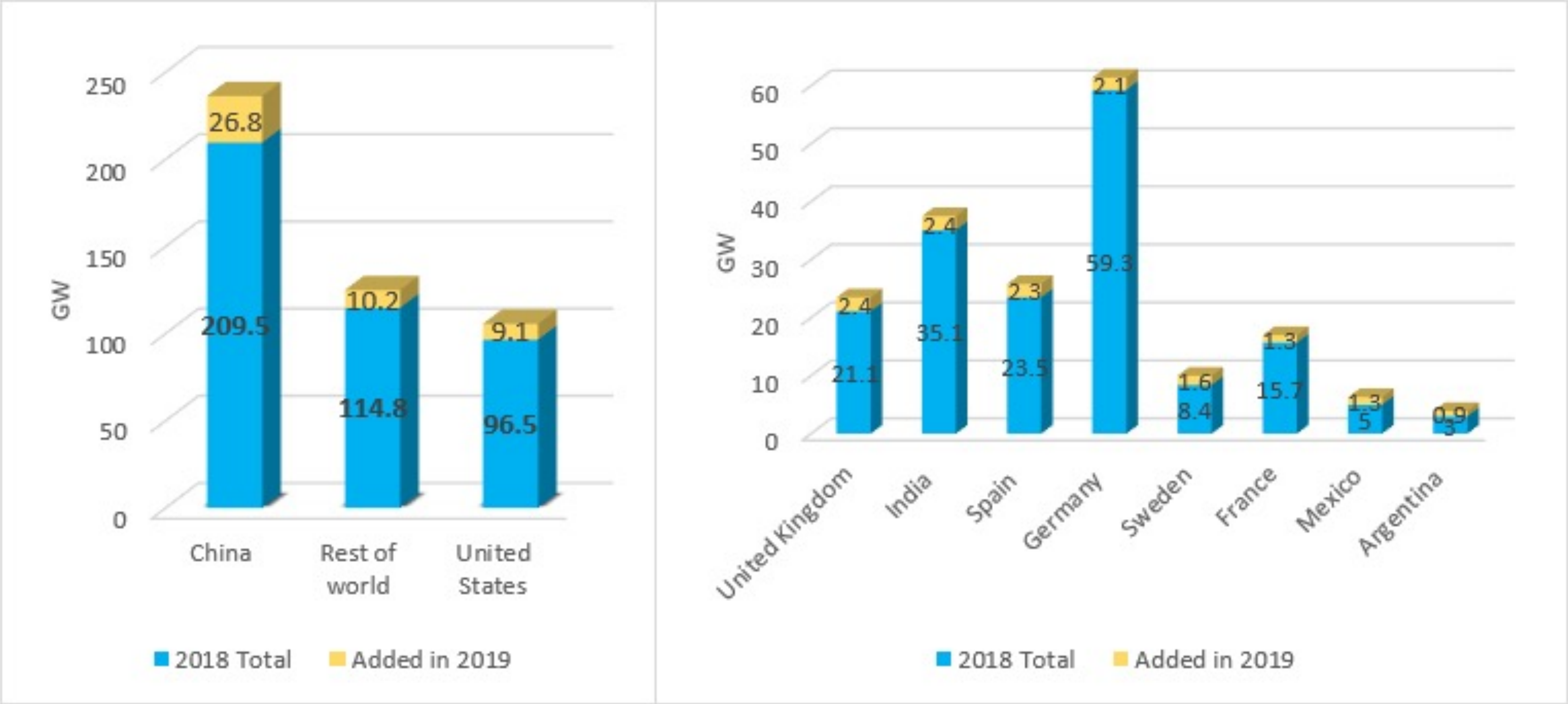
- The global wind power market expanded approximately 20% in 2019, with around 60 GW of new capacity added to the world's electric grids (including more than 54 GW onshore and over 6 GW offshore).

Source [1] : REN21. 2020. Renewables 2020 Global Status Report (Paris: REN21 Secretariat). ISBN 978-3-948393-00-7

Introduction

Wind Power Worldwide

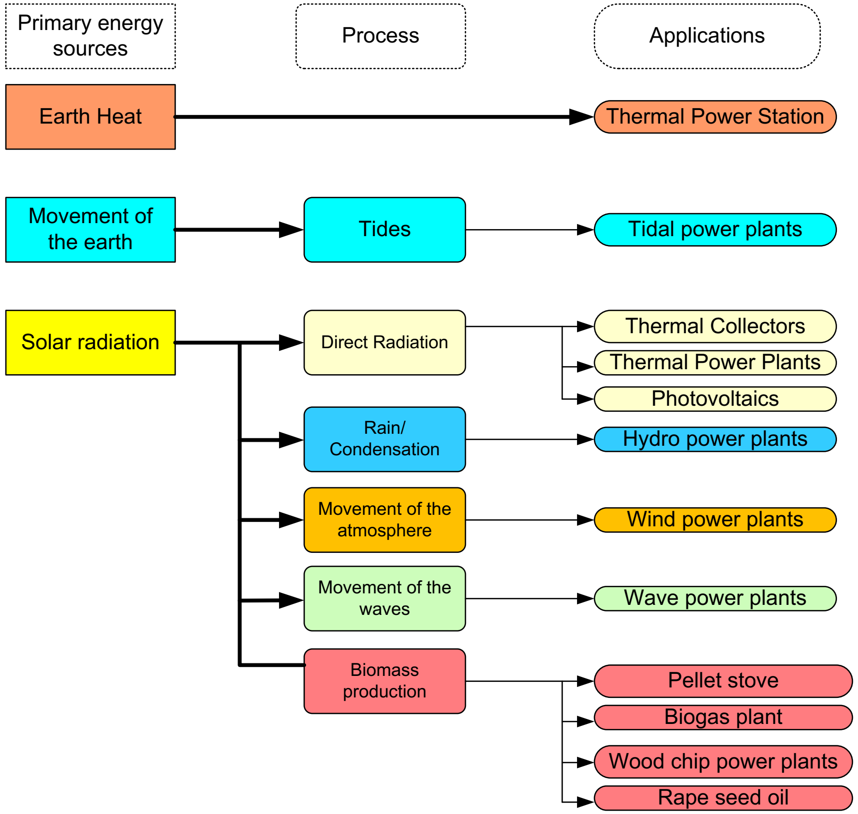
- Wind Power Capacity and Additions, Top 10 Countries, 2019



Source [1] : REN21. 2020. Renewables 2020 Global Status Report (Paris: REN21 Secretariat). ISBN 978-3-948393-00-7

Introduction

Family of Renewable Energies: Wind Power Origin

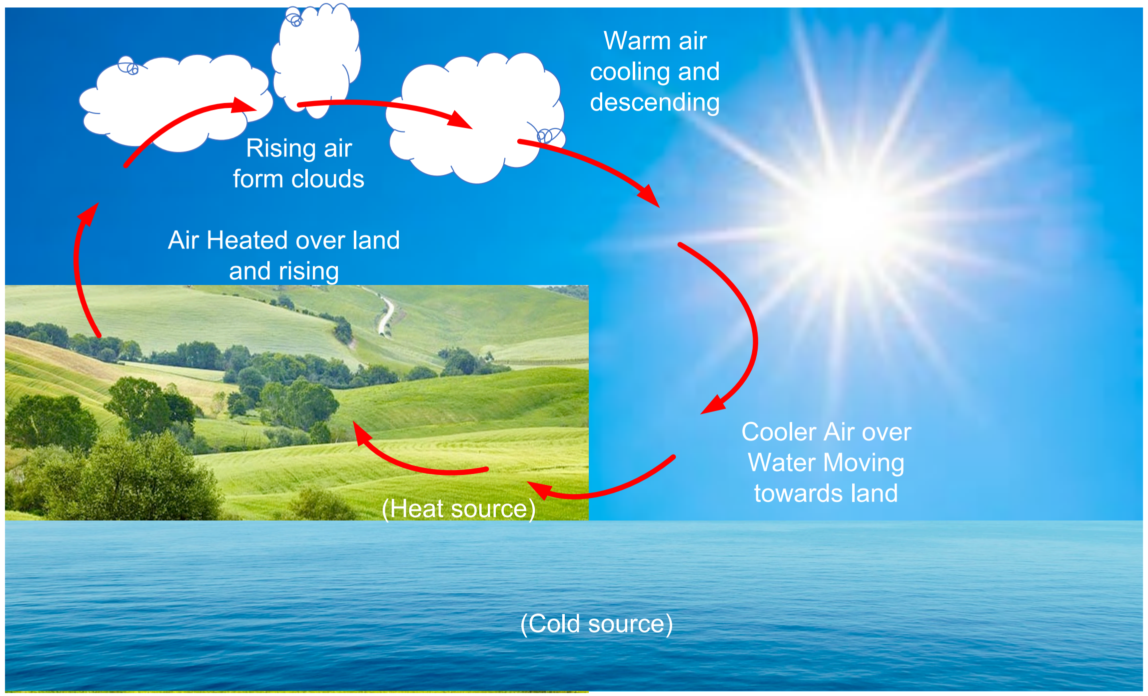


Primary energy sources
Process
Applications

Earth Heat → Thermal Power Station

Movement of the earth → Tides → Tidal power plants

Solar radiation
- Direct Radiation → Thermal Collectors, Thermal Power Plants, Photovoltaics
- Rain/ Condensation → Hydro power plants
- Movement of the atmosphere → Wind power plants
- Movement of the waves → Wave power plants
- Biomass production → Pellet stove, Biogas plant, Wood chip power plants, Rape seed oil



Solar radiation is the basis for a surprising range of energies

Atmospheric movement originates mostly due to solar radiation, which is also the basis for the **use of wind power**.

K. Mertens, Photovoltaics: fundamentals, technology, and practice, John Wiley & Sons, 2018

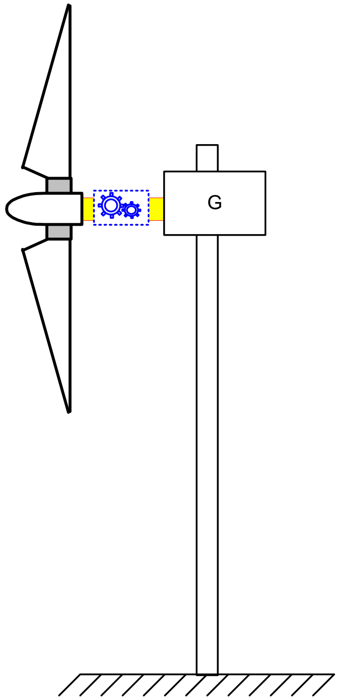
Introduction

Classification of Wind Turbines

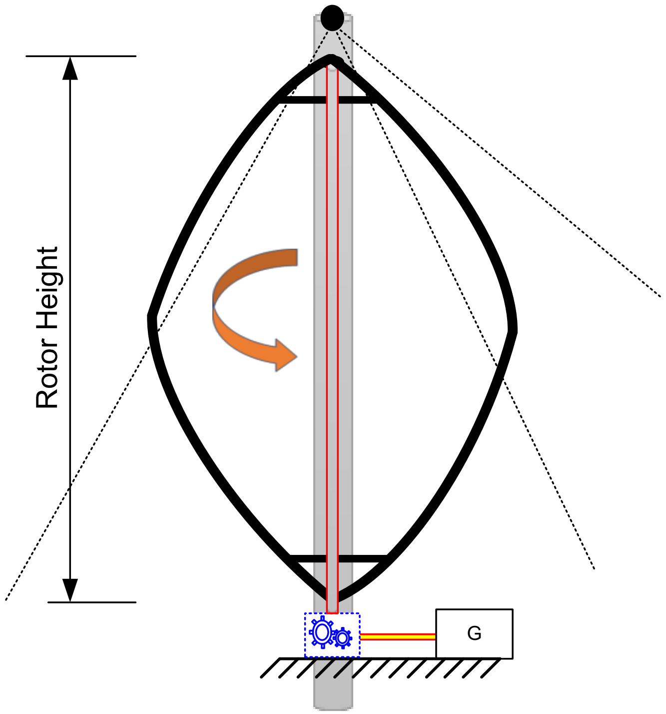
○ Types of wind turbine:

- Horizontal axis wind turbine (HAWT)

- Vertical axis wind turbine (VAWT)



HAWT

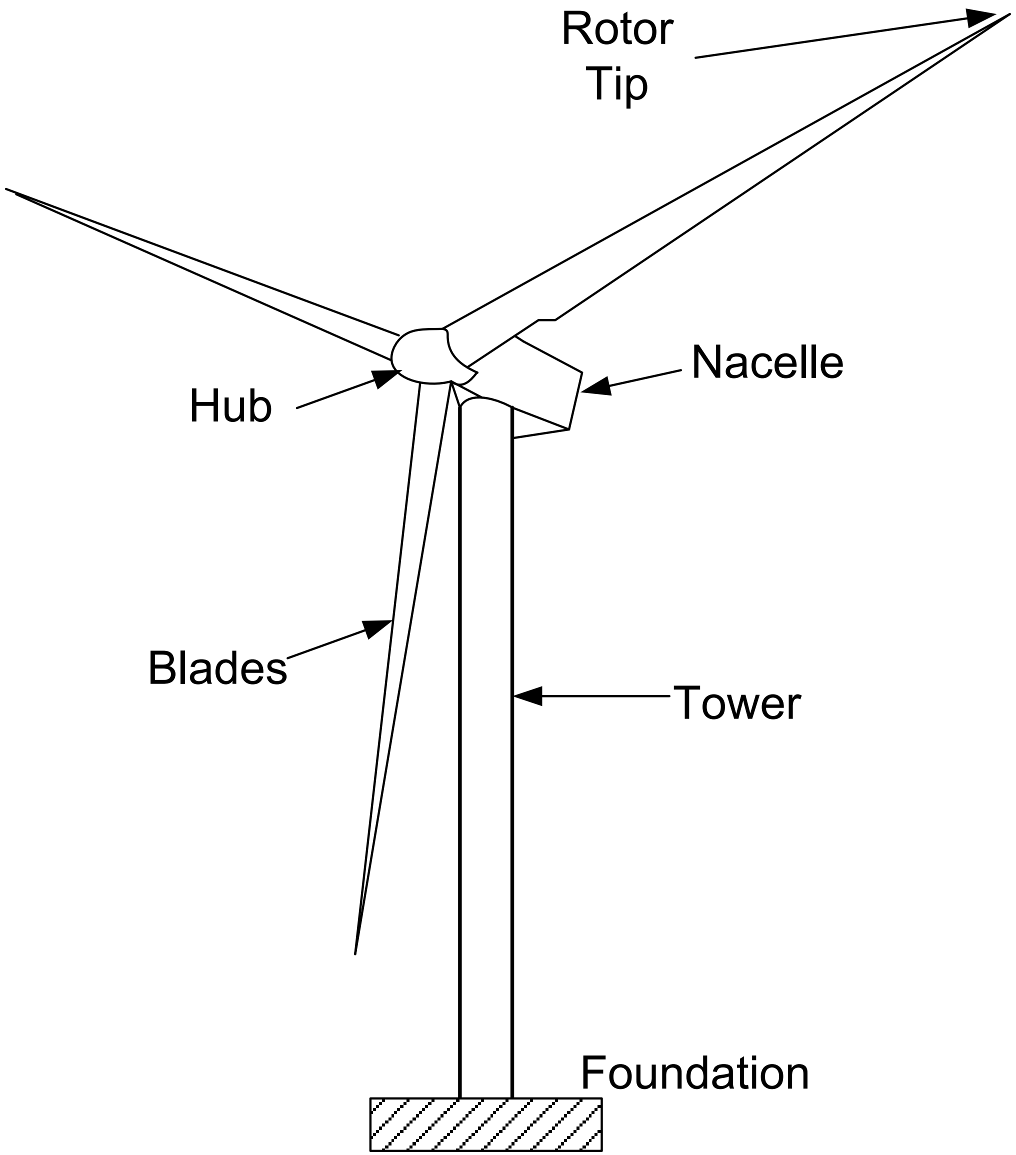


VAWT

Introduction

Wind Turbine Subsystems

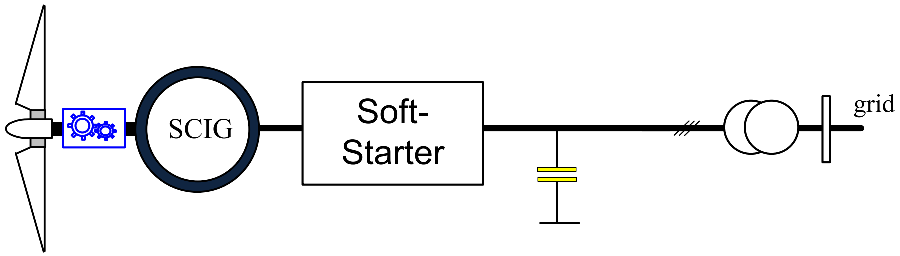
- Foundation
- Tower
- Nacelle
- Hub & Rotor



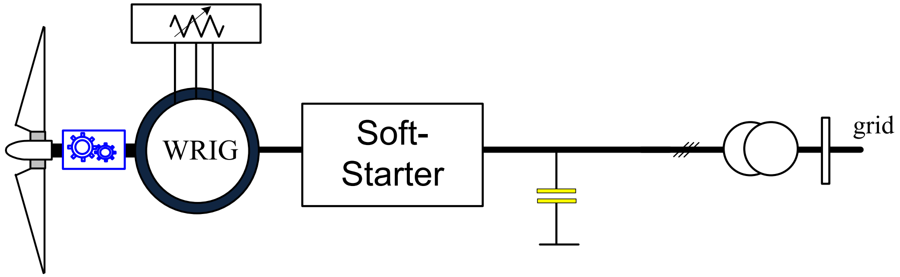
Introduction

Types of Wind Generation Systems

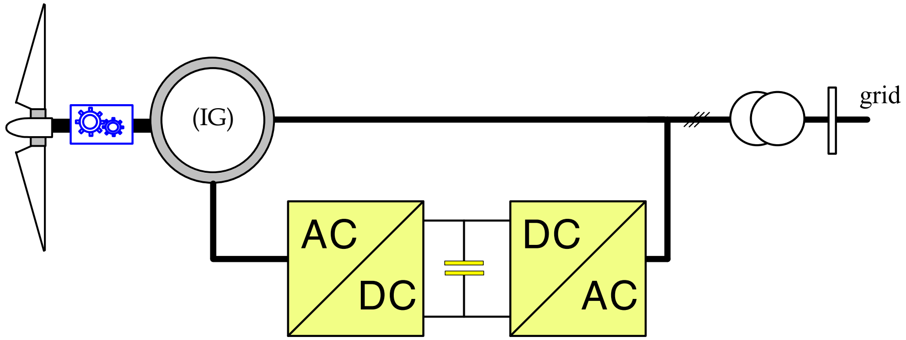
○ As wind energy consumption has increased, wind turbine concepts and generator types have been developed and improved. Various wind turbines (WTs) and generator systems have been built for the market



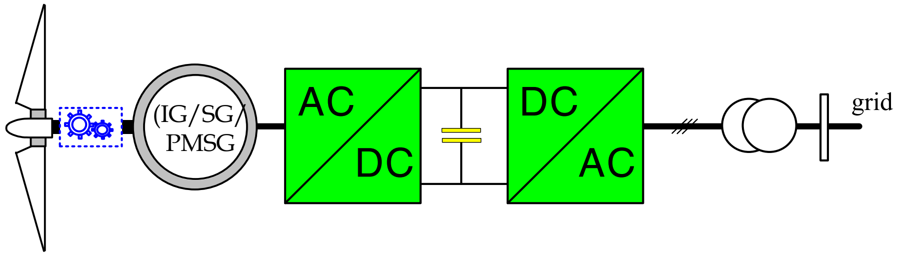
Type A



Type B



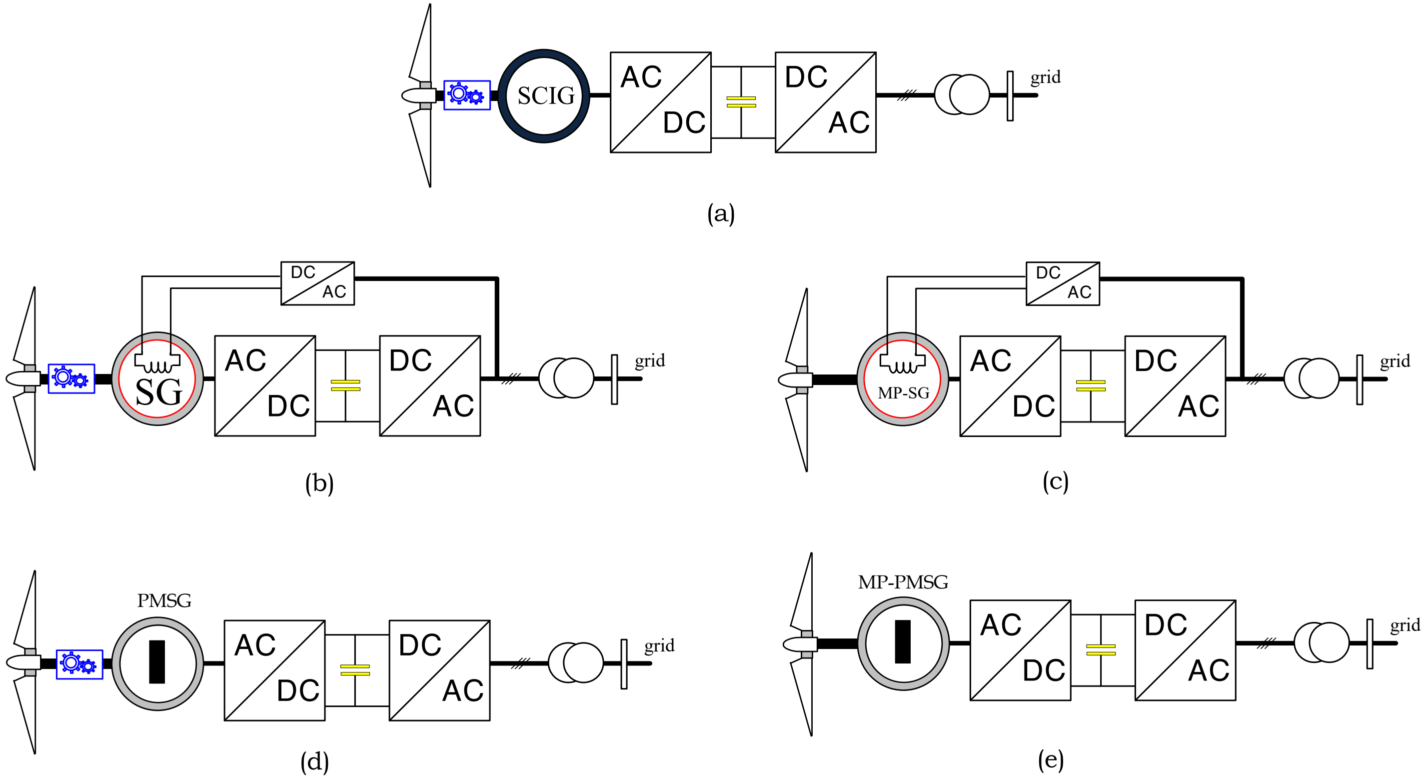
Type C



Type D

Introduction

Types of Wind Generation Systems:full scale variable speed wind turbine



(a)

(b)

(c)

(d)

(e)

(a) full scale with a squirrel cage induction generator,(b) full scale with a synchronous generator ,(c) full scale with a multi-pole synchronous generator ,(d) full scale with permanent magnet synchronous generator and (e)full scale with a multi-pole permanent magnet synchronous generator

Section Outline

In this section the aerodynamics of Wind Turbines is discussed. The topics that will be covered as follows: Kinetic Energy of Wind, Air Density, Impact of Friction and Height on Wind Speed, Wind Turbine Blades, Angle of Attack, Pitch Angle, Coefficient of Performance, Tip Speed Ratio (TRS), Tracking the maximum Cp and Separation of Wind Turbines.

Section 7.2

Aerodynamics of Wind Turbines

Aerodynamics of Wind Turbines

Concept of work power and energy

- Work is defined as force multiplied by displacement.
- Power is the rate at which work is done. It is the work/time ratio.

$$\text{Power} = \frac{\text{Work}}{\text{Time}} = \text{Force} \times \frac{\text{Displacement}}{\text{Time}}$$

$$\text{Power} = \text{Force} \times \text{Velocity}$$

Aerodynamics of Wind Turbines

Kinetic Energy of Wind

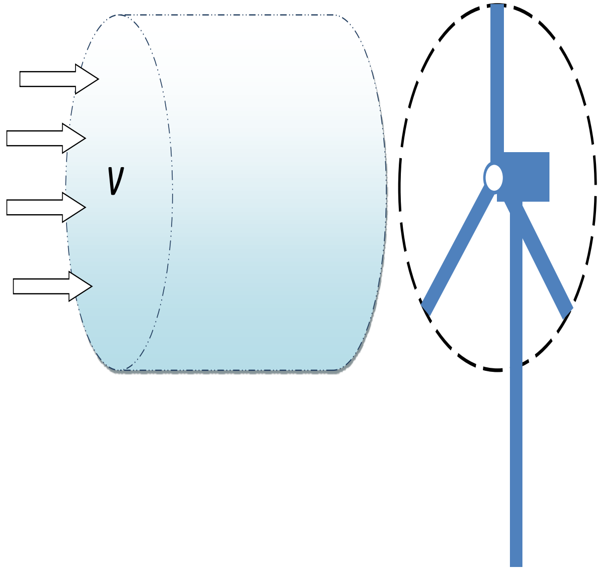
- Wind turbines are designed to absorb the kinetic energy of the wind and transform it to electrical energy

v

- The kinetic energy of wind is given as

$$K.E. = \frac{1}{2} m\upsilon^2$$

where K.E. denotes the kinetic energy of the air packet (Ws), m denotes the mass of the air (kg), and v denotes the wind velocity (m/s).



- The mass of air travelling through a given area

$$m = A \times \rho \times \upsilon \times t$$

Aerodynamics of Wind Turbines

Kinetic Energy of Wind

- The wind power (P_{wind}) in watt can be expressed as

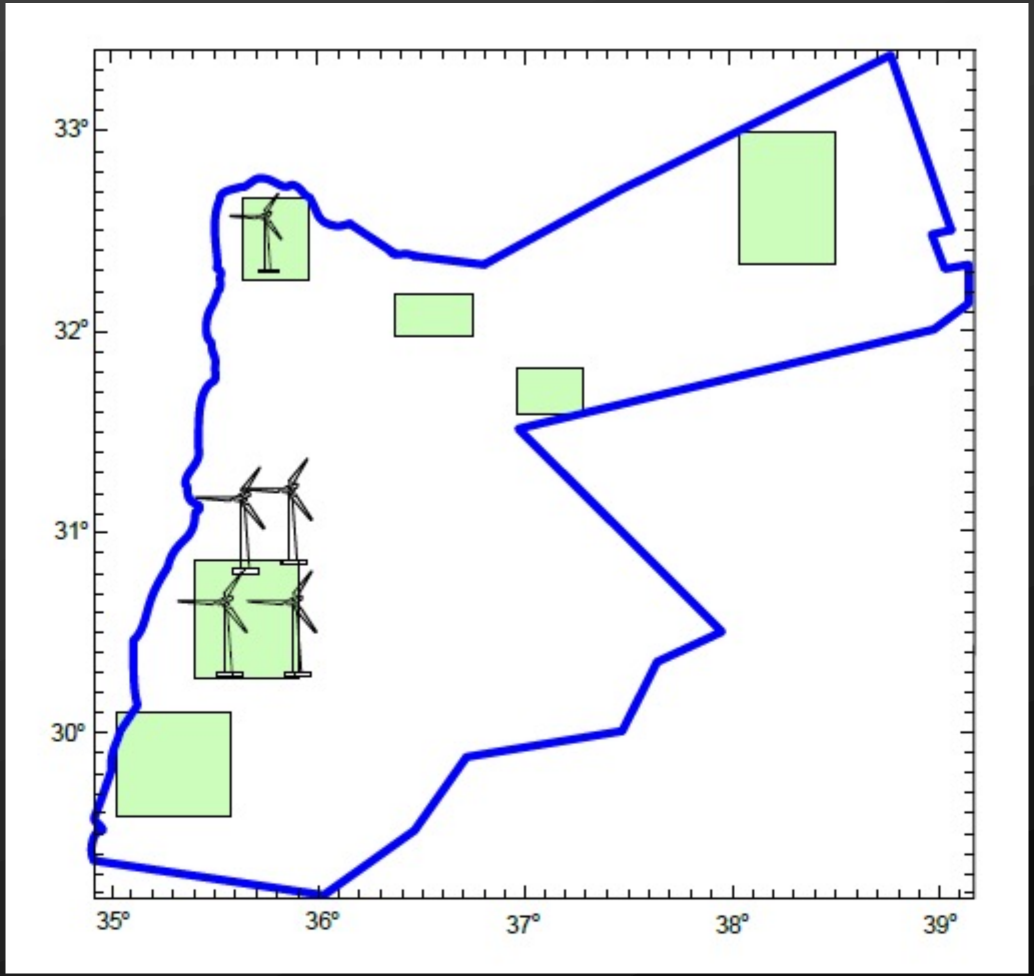
$$P_{wind} = \frac{\text{K.E.}}{t} = \frac{1}{2}\text{A}.\rho.\upsilon^3$$

- The specific power or power density

$$\text{p} = \frac{P_{wind}}{A} = \frac{1}{2}\rho.\upsilon^3$$

Wind Map of Jordan - Promising Locations

- a map of the average wind speed in Jordan at 50 m height.
- Several areas in the east and west regions have fresh to strong winds with an average wind speed of about 8.0-10.0 m /s.



Aerodynamics of Wind Turbines

Air Density (ρ)

- Several factors affecting the Air density, and hence power in the wind, such as atmospheric pressure, temperature, humidity, elevation and gravitational acceleration.

$$\rho = \frac{p_r}{\mu T} e^{\left(-\frac{gh}{\mu T}\right)}$$

$$\rho = \frac{353}{T + 273} e^{\left(-\frac{h}{29.3(T + 273)}\right)}$$

where:
P_r : the atmospheric pressure at sea level
T is the air temperature
μ is the specific gas constant
g is the gravitational acceleration
h is the elevation above the sea level
ρ is air density in kg/m3

Aerodynamics of Wind Turbines

Air Density (ρ)

- Example: If Al karak city is 900 meters above the sea level and its average wind speed is about 13 meters per second at 50 meters above ground level. The city's average temperature is 17°C. Determine the wind power density based on these average values.
- *Solution:*
- The air density

$$\rho = \frac{353}{T+273} e^{\left(-\frac{h}{29.3(T+273)}\right)} = 1.089\ \mathrm{kg/m^2}$$

- The power density

$$\text{Power density} = \frac{1}{2}\rho.\upsilon^3 = 1.196\ \mathrm{kW/m^2}$$

Aerodynamics of Wind Turbines

Air Density (ρ)

- **Example:** Determine the power density of wind with air temperature is 30°C and the speed of 12 m/s. if the area is 350 m above sea level.
- *Solution:*
- The air density

$$\rho = \frac{353}{30+273} e^{\left(-\frac{350}{29.3(30+273)}\right)} = 1.12\ \mathrm{kg/m^2}$$

- The power density

$$\text{Power density} = \frac{1}{2}\rho.\upsilon^3 = \frac{1}{2}\times 1.12\times 12^3 = 0.9677\ \mathrm{kW/m^2}$$

Aerodynamics of Wind Turbines

Air Density (ρ)

- **Example:** Considering the previous example, compute the wind power passing through a sweep area of 30 m blade.
- *Solution:*
- The area of the sweep area of wind turbine

$$A=\pi r^2=\pi\left(30\right)^2=2827.43\ \text{m}^2$$

- The power of wind in the specific sweep area

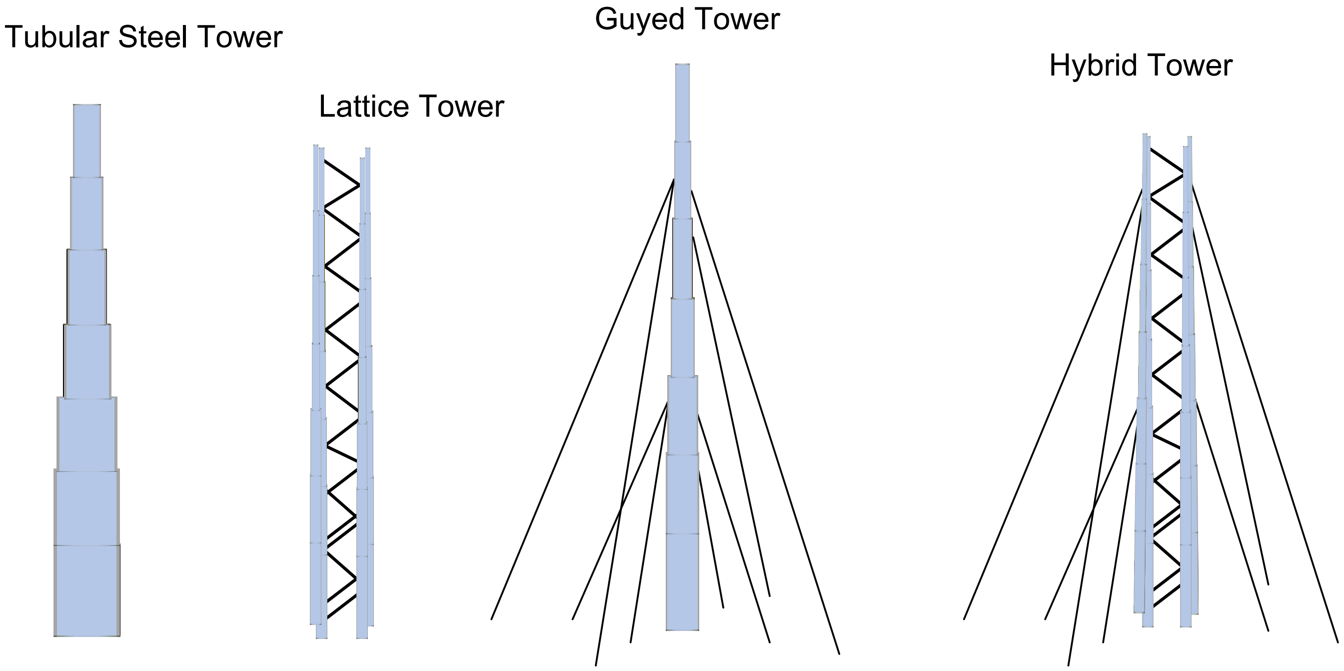
$$P_{\text{wind}}=\text{Area}\times\text{Power density}=1196\times 2827.43=3.381\ \text{MW}$$

Tower Design

- One of main aspect of wind plant design is the tower design.
- Several factors contribute to design criteria such as cost, safety, aesthetics, or a combination of all these factors.
- The installed capacity of the towers and their height have to be balanced against production and maintenance tower costs.
- The cost of tower accounts usually about 15–20% of the overall investment.

Tower Design

- Most towers for wind turbines are fabricated of steel. Recently, concrete towers were promoted, however, due to some circumstances and applications where production costs are competitive, their use is limited.
- Several steel tower designs are used such as steel tubular tower, lattice tower, hybrid tower, and guyed tower.
- Figure shows the general appearance of these design.



Aerodynamics of Wind Turbines

Impact of Friction and Height on Wind Speed

- Wind speeds decreases near ground as air friction is high
- Smooth surfaces, such as water, reduce air friction.
- Forests or buildings slow down the wind substantially
- An approximate method

$$\frac{\upsilon}{\upsilon_o} = \left(\frac{H}{H_o}\right)^{\alpha}$$

where α is a coefficient of friction, v is donates the wind speed at height of H and v_o is the wind speed at known height of H_o.;
typical values are α = 0.143 for an open terrain; α = 0.4 for a large city; and α = 0.1 for calm water

Aerodynamics of Wind Turbines

Impact of Friction and Height on Wind Speed

- The power of wind can be determined as

$$\frac{\mathrm{P}_{\mathrm{wind}}}{\mathrm{P}_{wind\_o}} = \left(\frac{\upsilon}{\upsilon_o}\right)^{3} = \left(\frac{H}{H_o}\right)^{3\alpha}$$

- **Example:** Compute the wind power density at 50 m in an open terrain if the wind power density at 100 m is 2.5 kW/m2 when wind speed is 10 m/s.
- Solution: For an open terrain, ɑ = 0.143

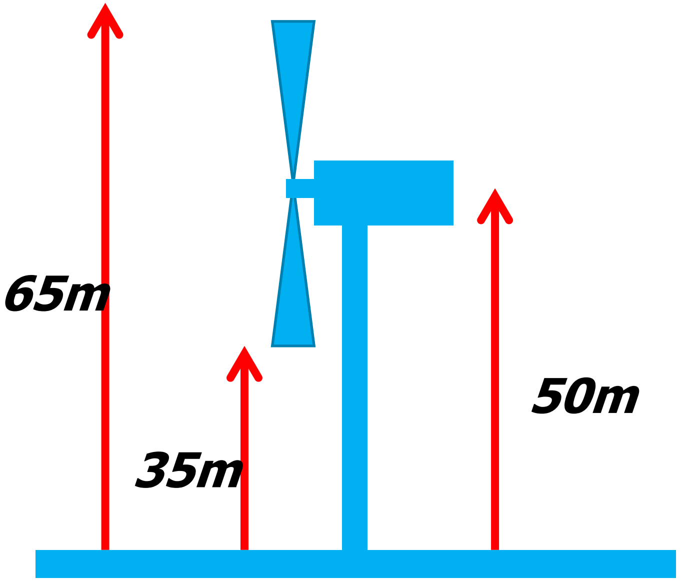
$$\text{Wind Power density} = \text{Wind powerdensity\_o} \times \left(\frac{\mathrm{H}}{\mathrm{H_o}}\right)^{3\alpha} = 2.5 \times \left(\frac{50}{100}\right)^{3\times 1.43} = 1.86\ \mathrm{kW/m^2}$$

Aerodynamics of Wind Turbines

Impact of Friction and Height on Wind Speed

- **Example:** A wind turbine with a 30 meter rotor diameter and a friction coefficient of 0.2 is installed with its hub 50 meter above the ground surface. Calculate the ratio of specific power in the wind at the peak point reached by a rotor blade tip to the lowest point reached by it.
- *Solution*:

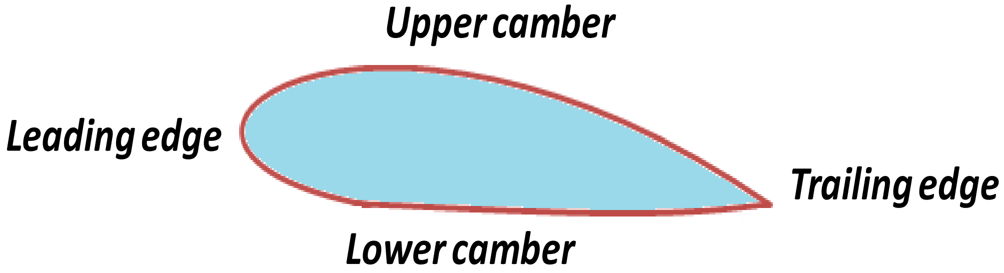
$$\frac{P_{wind}}{P_{wind\_o}} = \left(\frac{H}{H_o}\right)^{3\alpha} = \left(\frac{65}{35}\right)^{3\alpha} = 1.45$$



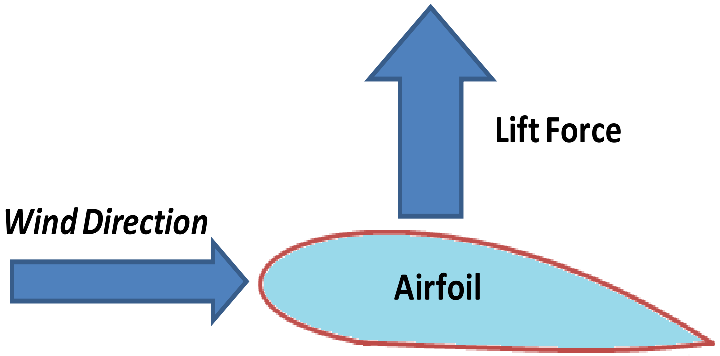
Aerodynamics of Wind Turbines

Wind Turbine Blades

- Wind turbine blade



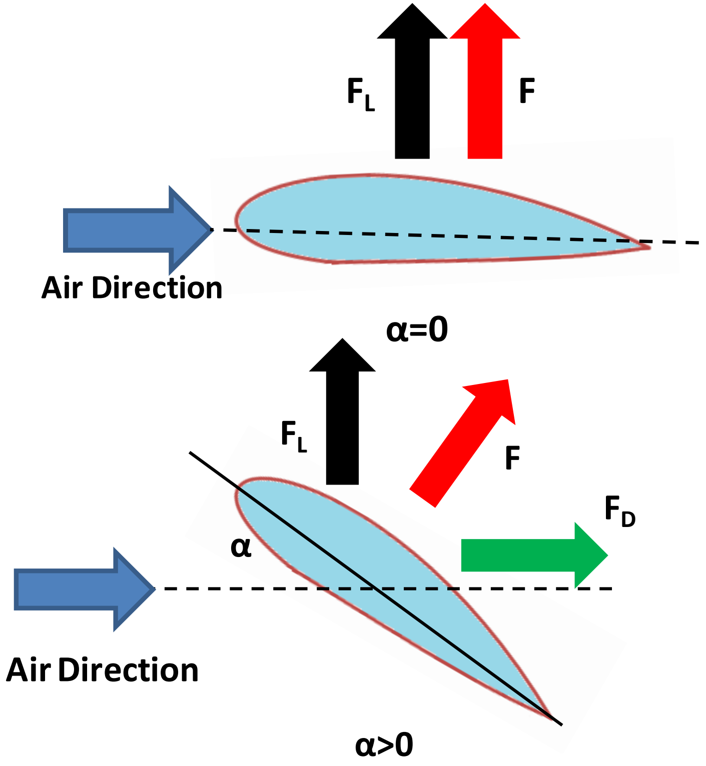
- Wind over the top of the airfoil travels more distance until it can reunite with the air under the airfoil that travels a shorter distance “Bernoulli's Principle”
- The net pressure of the lift $P_{net} = P_{r2} - P_{r1}$
- the aerodynamic force F $F = P_{net} A$



Aerodynamics of Wind Turbines

Angle of Attack

- • If the angle of attack α=0, the aerodynamic force will be lift force.



- If the angle of attack α>0
- The lift coefficient C_L and the drag coefficient C_D.

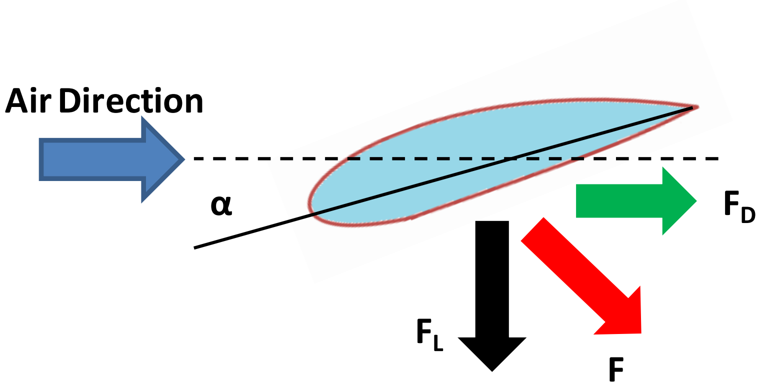
$$C_L = \frac{F_L}{F} \qquad C_D = \frac{F_D}{F}$$

- To absorb more energy from the wind, we need to raise C_L and reduce C_D.

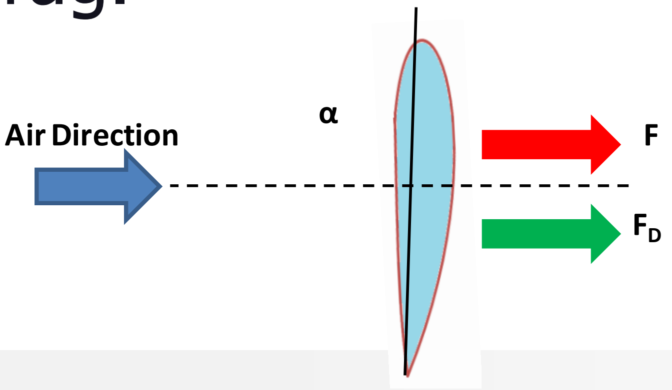
Aerodynamics of Wind Turbines

Angle of Attack

- If the angle of attack $\alpha<0$, the lift force (F_L) is reversed



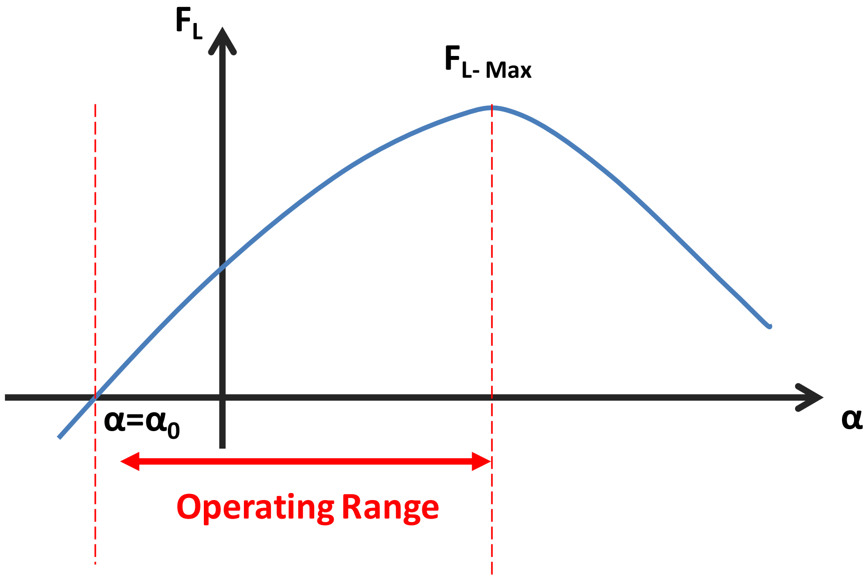
- If the angle of attack $\alpha= \alpha_o$, the lift force (F_L) is equal to zero and the entire aerodynamic force is drag.



Aerodynamics of Wind Turbines

Angle of Attack

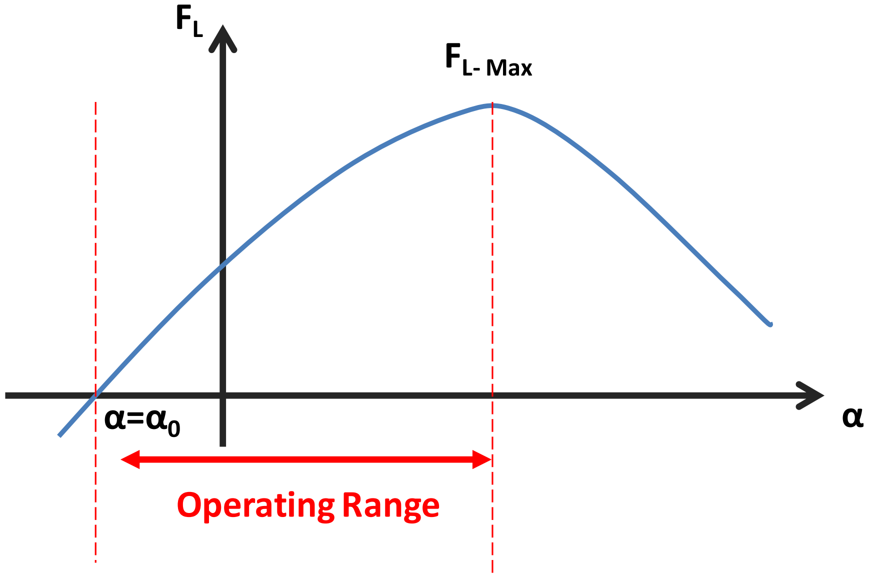
- for a negative angle *αo*, the lift force is zero. This is the feathering position of WTs (a position where FL is minimized).
- A larger negative angle would reverse the lift force.



Aerodynamics of Wind Turbines

Angle of Attack

- At $\alpha = 0$, the blade provides some lift.
- The lift increases when the angle of attack increases up to a limit. Beyond the maximum lift level, the increase in α reduces the lift while increasing the drag force.



Aerodynamics of Wind Turbines

Angle of Attack

- **Example:** A wind turbine with three-blades is operating at a given α and the aerodynamic force applied by wind on each blade is 2000 N and CL is 0.95 at the given α. If the distance from the center of gravity of the blade and the hub is 30 meters.
- • Calculate the torque produced by the turbine
- • Calculate the mechanical power produced by the blades if they rotate at 30r/min.

Aerodynamics of Wind Turbines

Angle of Attack

Solution:

The lift force

$$F_L = C_L F = 0.95 \times 2000 = 1.9 \text{ kN}$$

The total torque of three blade

$$T = 3F_L = 3 \times 1.9 \times 30 = 171 \text{ kN.m}$$

r is the distance from the hub to the center of gravity of the blade

The total generated power is

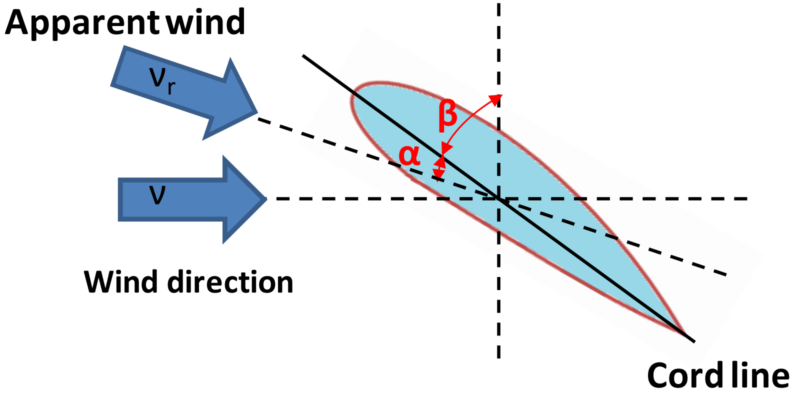
$$P = T\omega = 171\left(\frac{2\pi S}{60}\right) = 171\left(\frac{2\pi \times 30}{60}\right) = 537.2 \text{ kW}$$

ω and S are the angular and the rotation speed of the blades

Aerodynamics of Wind Turbines

Pitch Angle

- The pitch angle is the angle between the cord line of the blade and the vertical line representing the linear motion of the center of gravity.



- Increasing the pitch angle reduces the angle of attack and vice versa.
- Used to adjust the lift and drag forces to regulate the power collected from the wind in modern wind energy systems.

Aerodynamics of Wind Turbines

Pitch Angle

Example: Compute the angle of attack if the pitch angle is 5°, for a relative wind speed represented by $49\angle -73.31°$ m/s

Solution

The angle of the relative wind speed is −73.31°.

The angle of attack

$$\alpha + \beta = 90^o - 69.02^o = 20.98^o$$

$$\alpha = 20.98^o - 5^o = 15.98^o$$

Aerodynamics of Wind Turbines

Coefficient of Performance

- The coefficient of performance of a wind turbine, is

$$C_p = \frac{P_{blade}}{P_{wind}}$$

where P_{blade} is the wind power captured by the blade of the wind turbine and, P_{wind} is the total power available in the wind reaching the sweep area of the blades.

- The coefficient of performance depended on many key parameters including : 1) the wind speed 2) the rotational speed of the blade 3) angle of attack and 4) pitch angle.

Aerodynamics of Wind Turbines

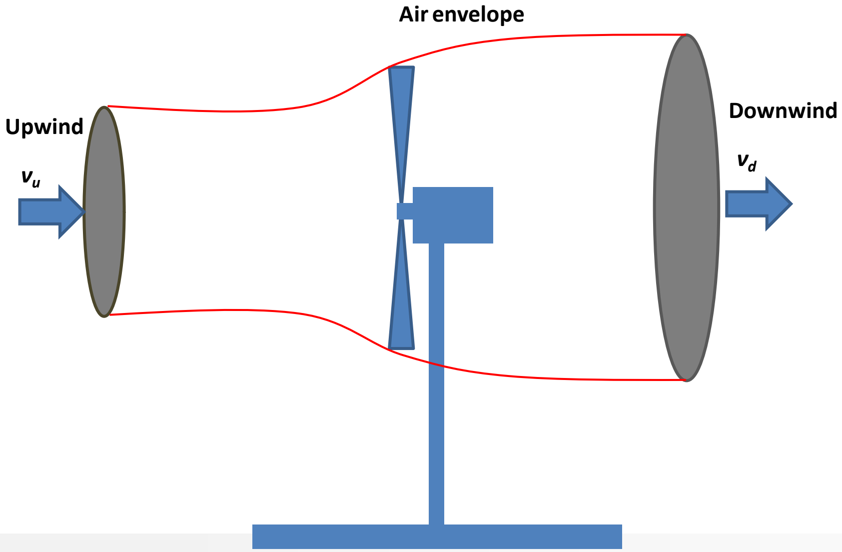
Coefficient of Performance

- The coefficient of performance

$$C_p = \frac{1}{2}(1+\gamma)\left(1-\gamma^2\right)$$

- where γ represents the ratio of the down-stream to the far up-stream wind speed

$$\gamma = \frac{\upsilon_d}{\upsilon_u}$$



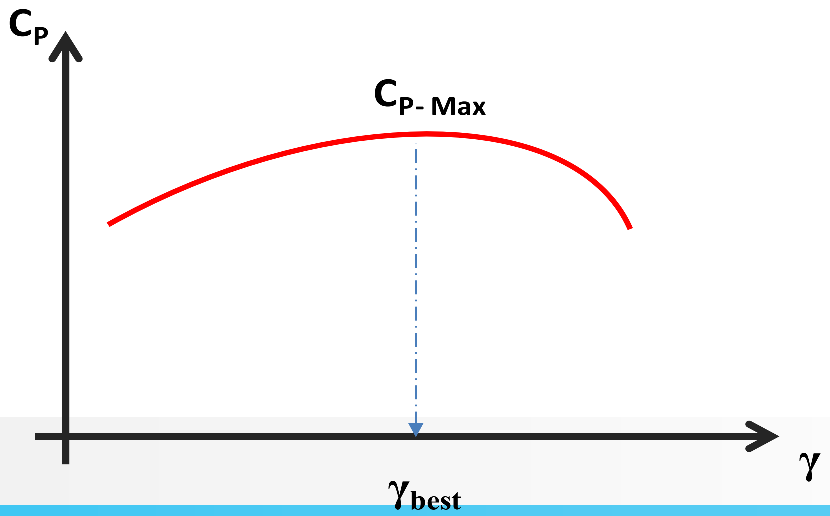
Aerodynamics of Wind Turbines

Coefficient of Performance

- To compute the maximum value of *Cp*, we need to equate the derivative to zero

$$\frac{dC_p}{d\gamma} = 0 \qquad \frac{dC_p}{d\gamma} = \frac{1}{2}\left(1+\gamma\right)\left(1-3\gamma\right) = 0$$

- The solution is γ_{best}=1/3 and the corresponding $C_{p\text{-}Max}$ =0.593 (also known as the "Betz Limit)

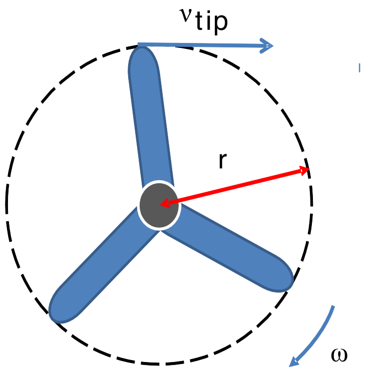


Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- the tip speed ratio (TSR) is a critical parameter. It is characterized as the ratio of the blade tip speed to the incoming wind speed.

$$\frac{\text{Rotor Tip Speed}}{\text{Wind Speed}} = \frac{\upsilon_{tip}}{\upsilon_{wind}}$$



- The tip speed (v_{tip}) denotes the linear velocity of the tip of the blade

$$\upsilon_{tip}(m/s) = \omega r = \frac{2\pi n r}{60}$$

Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- If TSR is high, the blades spins too fast (blade will experience turbulent wind).
- If TSR is low, the blades spins too slow (It could not efficiently capture the wind energy.)
- The optimal TSR gives the maximum efficiency that a turbine can extract wind energy.

Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- **Example:** If the tip of a wind blade is traveling at 45 m/s (161 km/h) and the wind speed is 9 m/s (32 km/h), obtain the tip-speed ratio.

- *Solution*

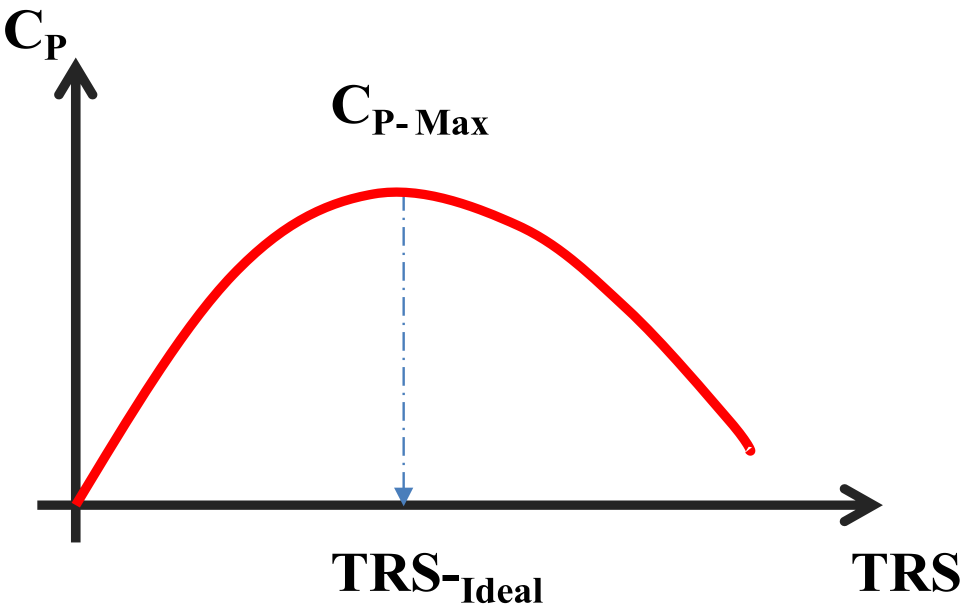
$$\mathrm{TSR} = \frac{\upsilon_{tip}}{\upsilon_{wind}} = \frac{161}{32} = 5$$

This means that the tip of the blade is traveling five times faster than the speed of the wind.

Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- When the blade set rotates in slow motion, much of the wind moves through the turbine without being collected by the blades.
- When the turbine rotates too fast, the blades will always pass through used or turbulent winds.



Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- Example: Consider a wind turbine with a sweep radius of 5 m and a tip speed ratio of 7. Assuming that wind turbine is designed to start producing power when the generator speed is above 905 r/min, which corresponds to a wind speed of 5 m/s. Find the ratio of the gear system.
- **Solution**
- The tip speed

$$\upsilon_{tip} = TSR \times \upsilon_{wind} = 7 \times 5 = 35 \text{ m/s}$$

- The shaft speed

$$n = \frac{\upsilon_{tip}}{2\pi r} = \frac{35}{2\pi \times 5} \times 60 = 67 \ \text{ r/min}$$

Aerodynamics of Wind Turbines

Tip Speed Ratio (TRS)

- The gear ratio

$$\frac{n_{gear}}{n} = \frac{905}{67} = 13.5$$

- **Example:** Calculate the tip speed ration for a 90-m-diameter turbine rotating at 15 rpm with a wind speed of 10 m/s?

$$\mathrm{r} = \frac{\mathrm{D}}{2} = \frac{90}{2} = 45 \text{ m}$$

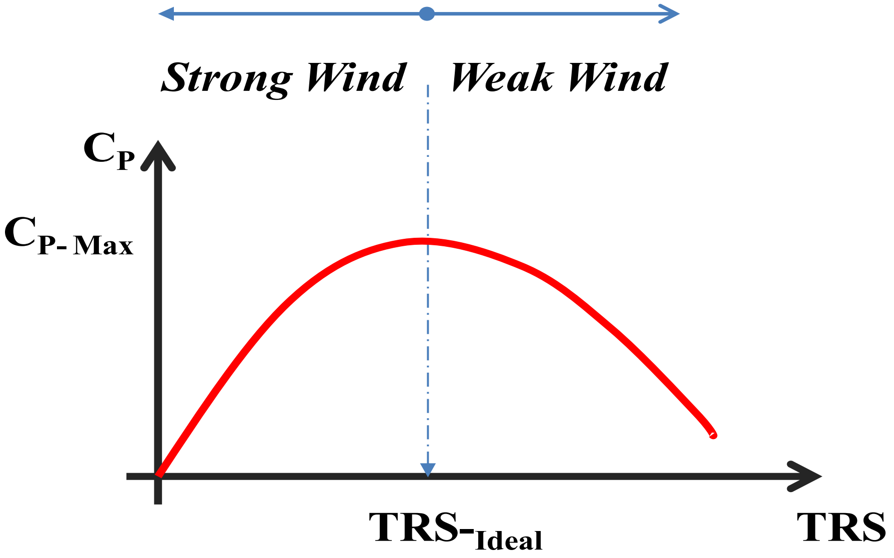
$$\omega = \frac{2\pi n}{60} = \frac{2\pi \times 15}{60} = 1.57 \text{ rad/s}$$

$$\mathrm{RST} = \frac{\upsilon_{tip}}{\upsilon_{wind}} = \frac{\omega r}{\upsilon_{wind}} = \frac{1.57 \times 45}{10} = 7.07$$

Aerodynamics of Wind Turbines

Tracking the optimal *Cp*

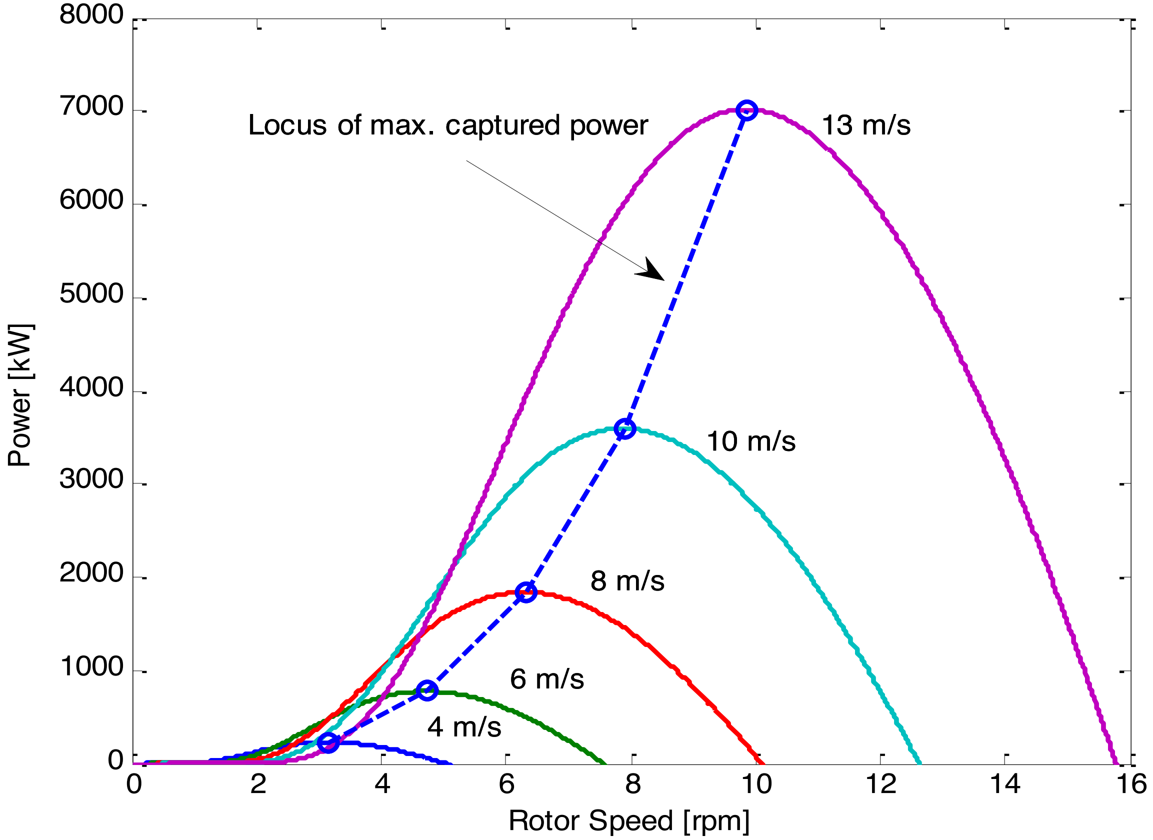
- For the case that the wind speed is stronger than TSR, The generator speed needs to be increased to track the ideal TRS value.
- For the case that the wind speed is weaker than TSR, The generator speed needs to be reduced to track the ideal TRS value.



Aerodynamics of Wind Turbines

Operational zones of wind turbine generator

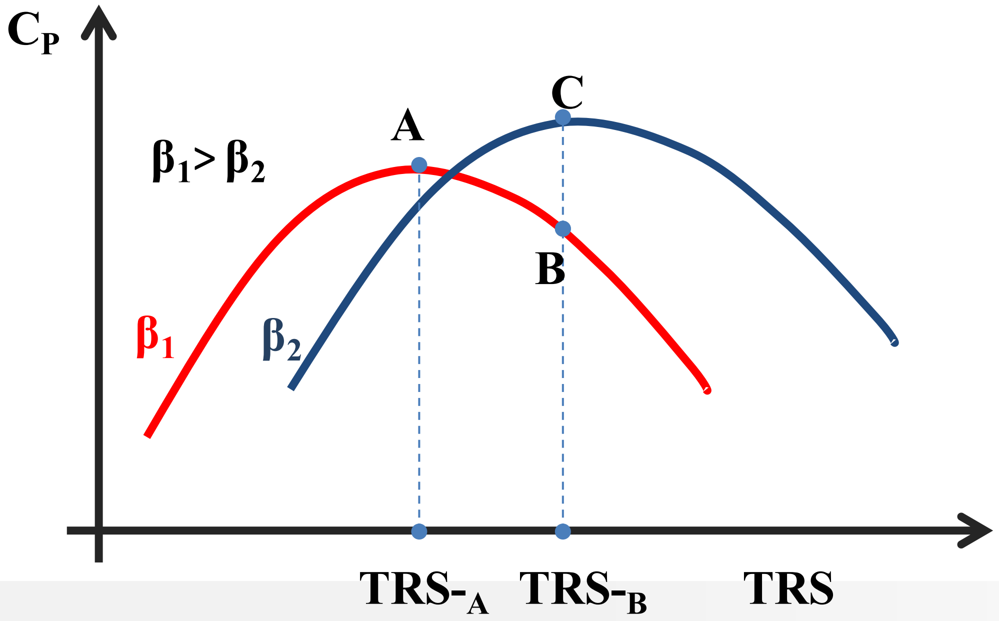
- Power-speed characteristics with maximum power point tracking



Aerodynamics of Wind Turbines

Tracking the maximum Cp

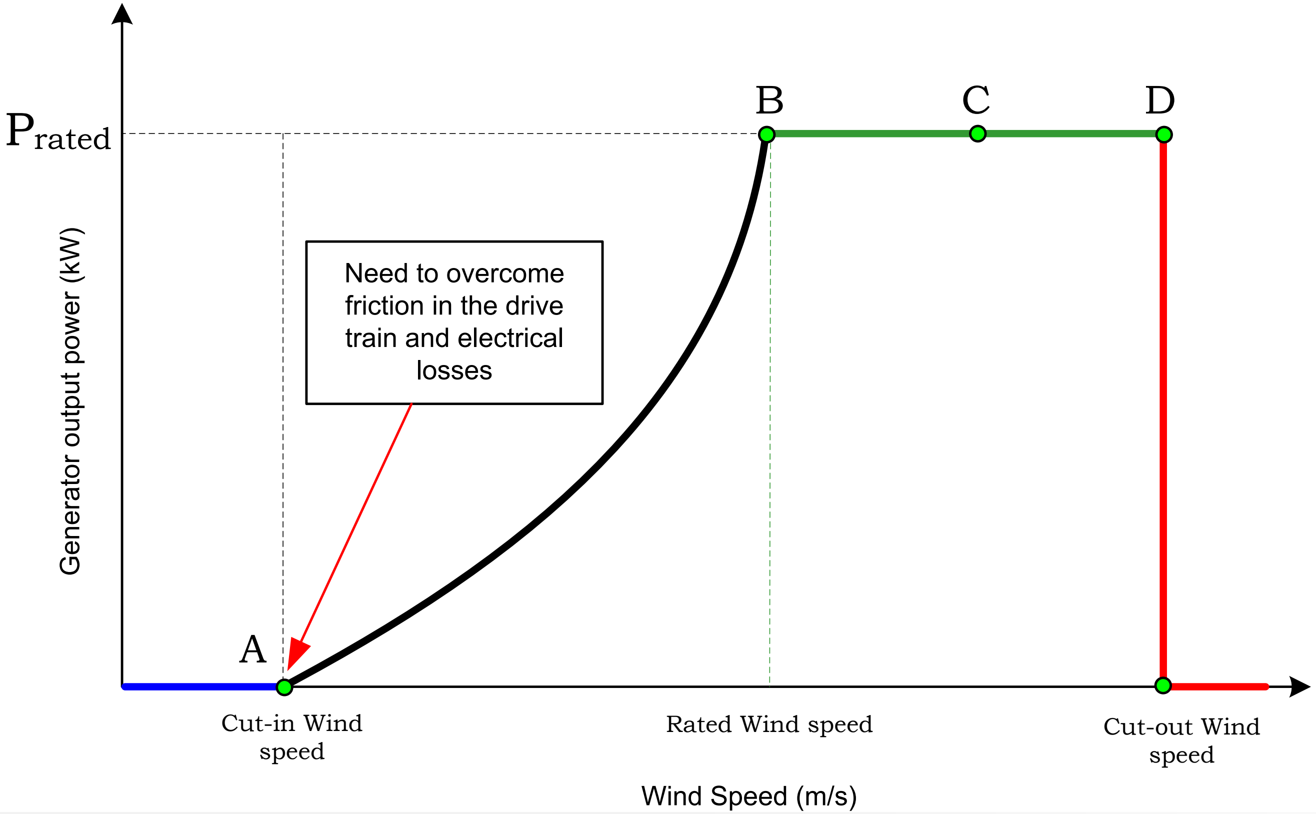
- Tracking the maximum C_p by changing the pitch angle.
- If wind speed is decreased so that the operating point is moved from A to B (on β_1 curve). It's possible to operate at highest Cp (where C point is located) by reducing the pitch angle β_2 (by increasing the angle of attack).



Aerodynamics of Wind Turbines

Operating characteristic of a wind turbine

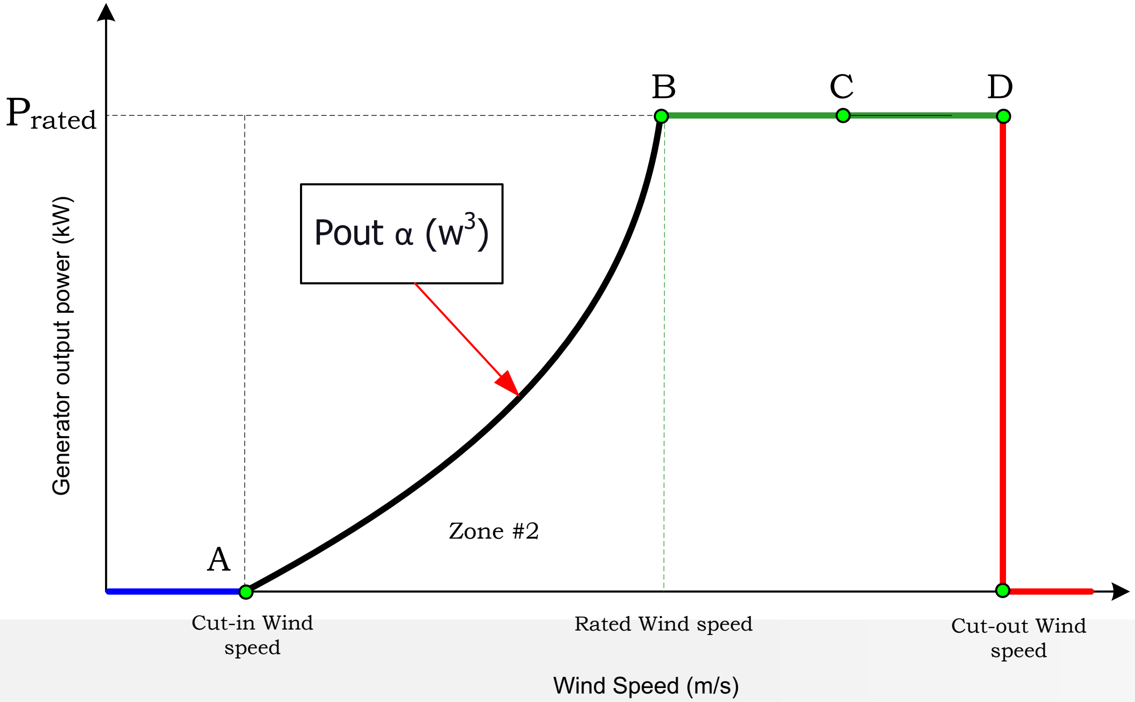
- At point A, the speed of the wind is strong enough to begin producing electricity. Wind speed at this point is called cut in speed or minimum speed (ω_{min}).



Aerodynamics of Wind Turbines

Operating characteristic of a wind turbine

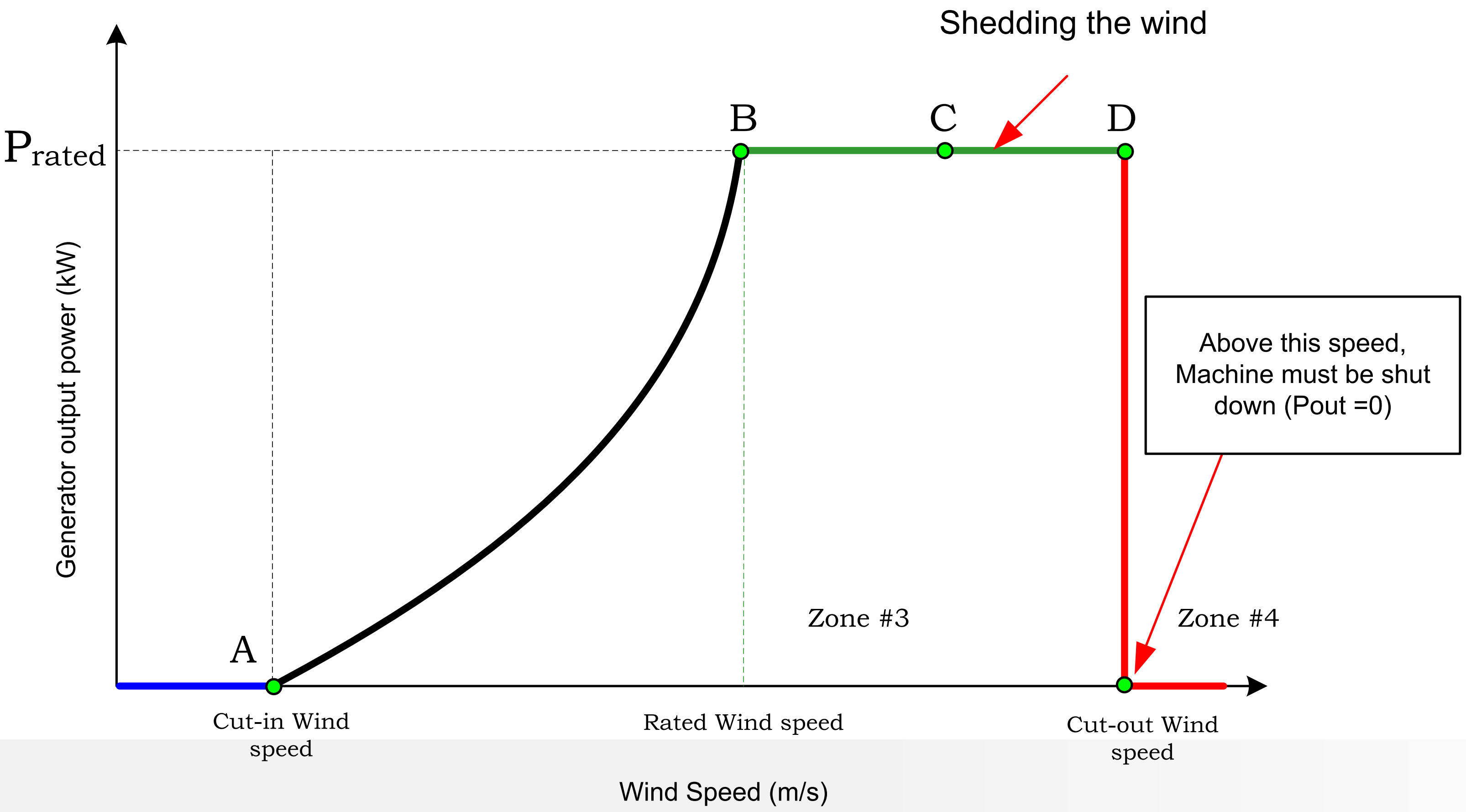
- Between the points A and B, the output of the turbine is the function of the cube of wind speed as well as the pitch angle.
- When the wind speed reaches (ω_B), the system must expel some of the wind energy to operate the turbine within its rated capacity.



Aerodynamics of Wind Turbines

Operating characteristic of a wind turbine

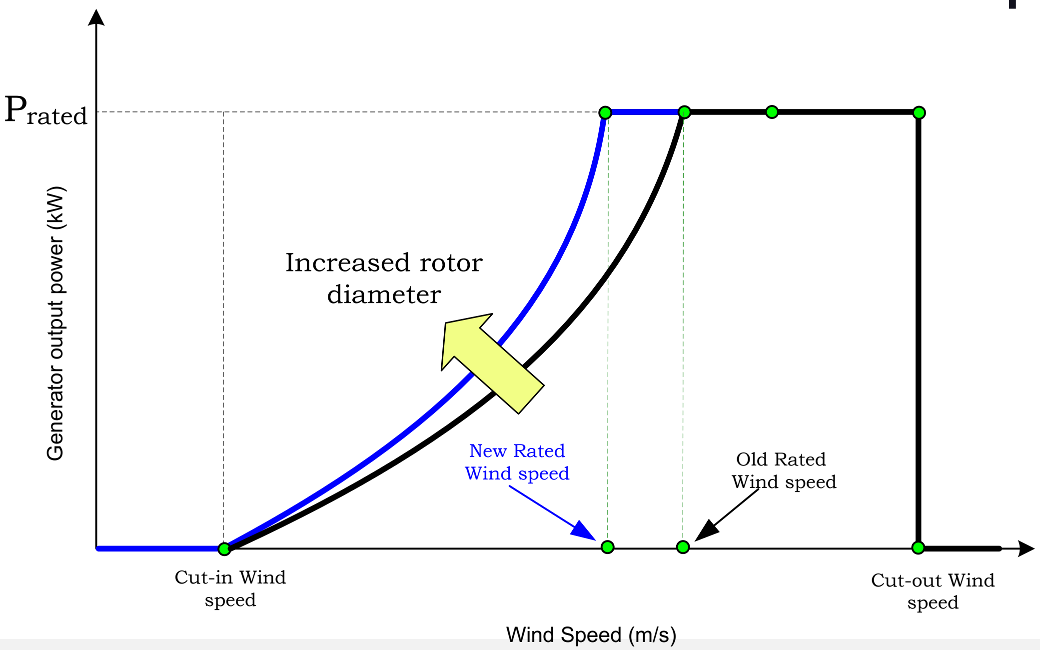
- At point D, the maximum permissible wind speed (ω_{max})- is termed a cut-out speed, Once reached, the turbine initiates to feather its blades.

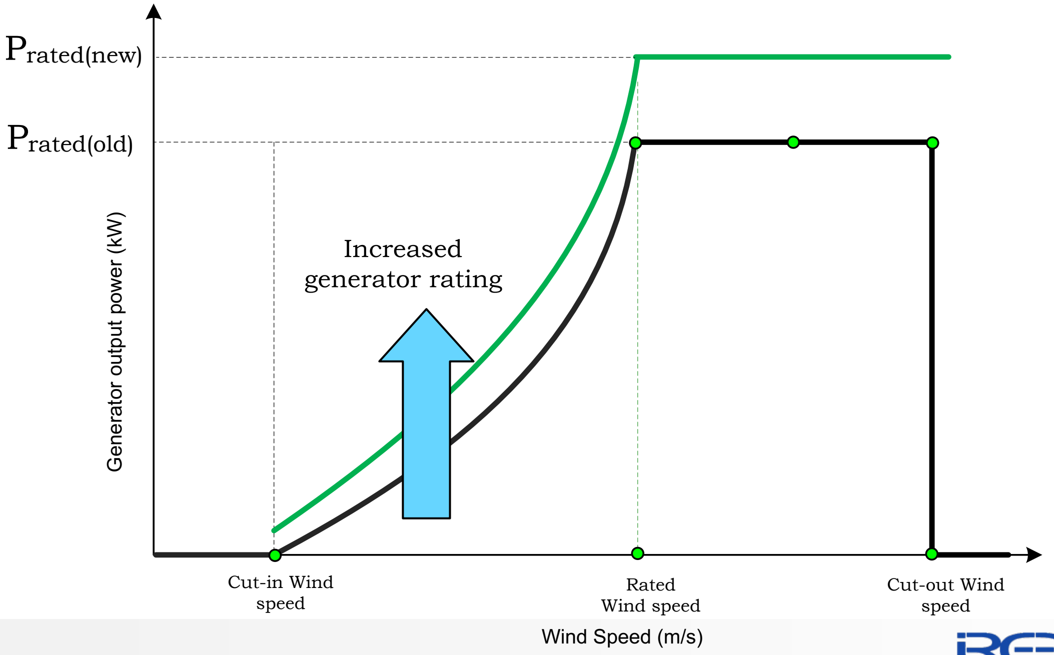


Aerodynamics of Wind Turbines

Rotor Diameter vs. Generator Rated Power

- Increasing the rotor diameter, with same generator, the rated power is obtained at lower wind speed.
- Increasing the generator rating, with same rotor diameter, the power is increased to the new rated power.

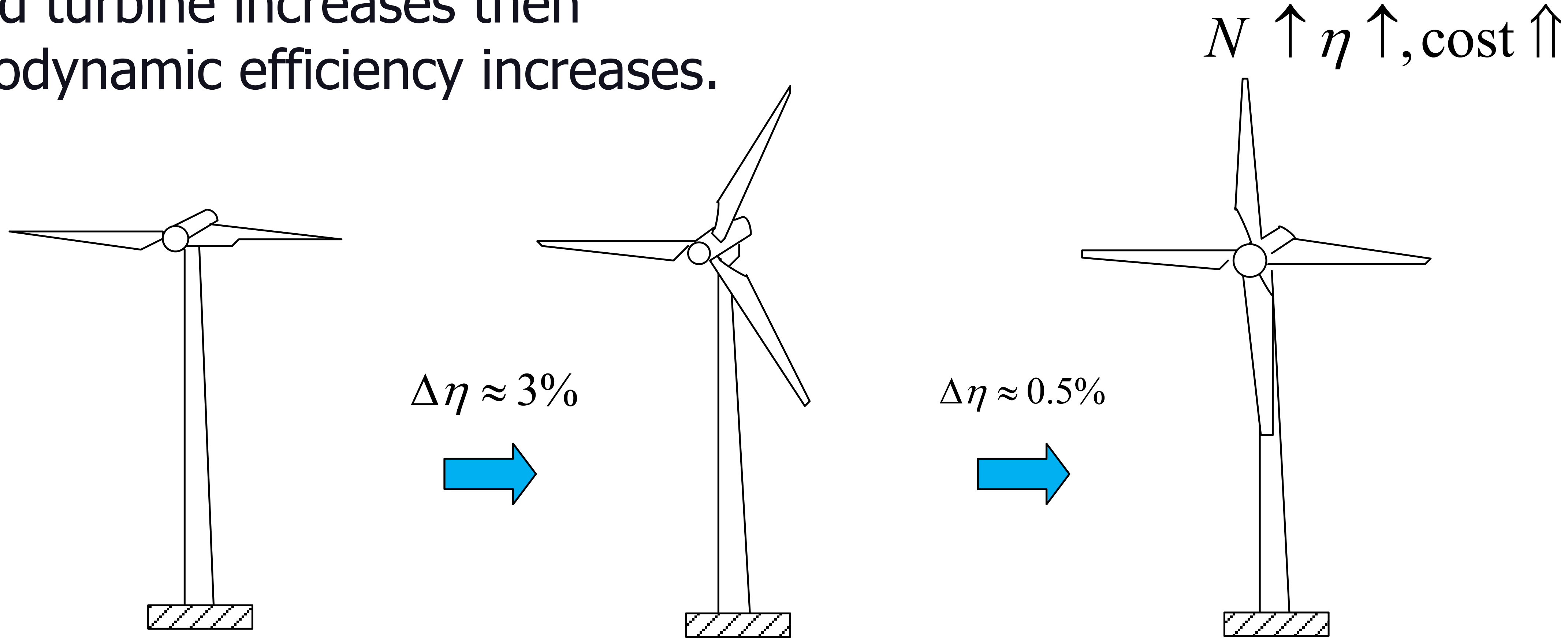




Aerodynamics of Wind Turbines

Blade Configurations

- When number of blades in the wind turbine increases then aerodynamic efficiency increases.



$N\uparrow \eta\uparrow, \text{cost} \Uparrow$

$\Delta\eta \approx 3\%$

$\Delta\eta \approx 0.5\%$

Aerodynamics of Wind Turbines

Separation of Wind Turbines

- Clustering wind turbines within wind farms has several advantages:
  - Reduces the installation costs
  - Reduces operation costs
  - Reduces maintenance costs
  - Simplifies grid connection
- The downside of the clusters:
  - The strong influence of wind instability.
  - The reduction of wind speed as it passes through the blades.
  - The creation of air turbulences.

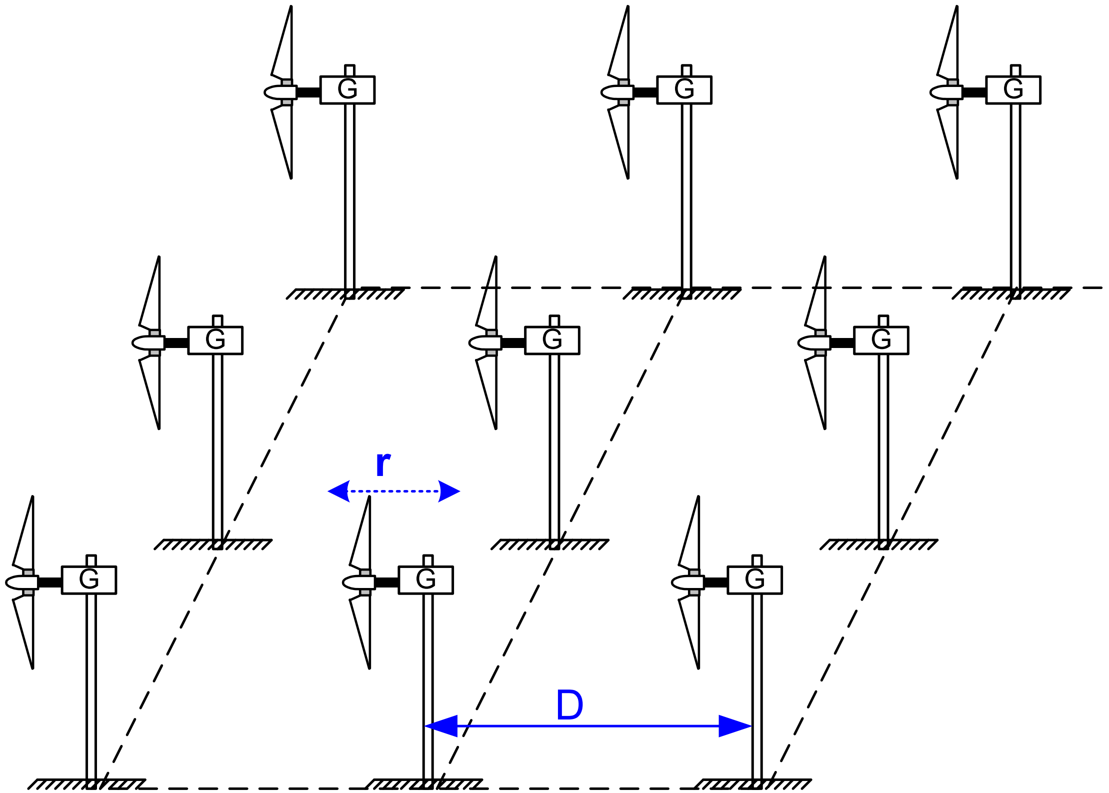
Aerodynamics of Wind Turbines

Separation of Wind Turbines

- One arrangement of WTs is the square configuration

- The separation factor S

$$S = \frac{D}{2r}$$



Aerodynamics of Wind Turbines

Separation of Wind Turbines

- The empirical array efficiency

$$\eta_{array} = 100\left(1 - ae^{-bs}\right)$$

Where a and b are constants values that depend on the number of turbines in the array

- The minimum land area

$$A_{land} = \left(xD - D + 2r\right)^2$$

where x is the number of turbine in one row

Aerodynamics of Wind Turbines

Separation of Wind Turbines

Example: How many WTs of 50 m blade length can be installed at the site of 10 × 10 km while achieving a separation factor of 800

Solution:

The distance between towers

$$D = 2rS = 100 \times 800 = 800 \text{ m}$$

The number of WTs in each row or column=13 turbines using

$$A_{land} = \left(800x - 800 + 2 \times 50\right)^2 = 10^8$$

For the whole site, the number of turbines

$$N_{Total} = 13 \times 13 = 169$$

Aerodynamics of Wind Turbines

Separation of Wind Turbines

Example: For the wind farm in the previous example, Compute the power production per land area when the wind power density at the hub is 400 W/m2, the coefficient of performance is 0.3, and the overall efficiency of the turbine-generator system is 85%. Assume the array efficiency is 74%.

Solution:

- The wind power

$$P_{wind} = \rho A_{blade} = 400\left(\pi \times 50^2\right) = 3.14\text{MW}$$

Aerodynamics of Wind Turbines

Separation of Wind Turbines

The output power

$$P_{out} = \eta \times P_{blade} = \eta \times C_p \times P_{wind} = 800\ \text{kW}$$

The total power of the turbines in the farm

$$P_{Total} = n \times P_{out} = 169 \times 800 = 135.2\ \text{MW}$$

The output power of the farm

$$P_{Farm} = \eta_{array} \times P_{Total} = 135.2 \times 0.74 = 100.05\ \text{MW}$$

The power production per land area

$$\frac{P_{Farm}}{\text{land area}} = \frac{100.05 MW}{10 km \times 10 km} \approx 1 \frac{MW}{km^2}$$

Thank You

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Introduction to Renewable Energy

Lecture x: Wind Turbines operation and Control

Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

Co-funded by the
Erasmus+ Programme
of the European Union

Section Outline

○ In this section, an introduction on wind turbine electrical components is discussed. The topics that will be covered as follows: Wind Turbines Components ,Types of Wind Turbine Generators, Types of wind turbine generator systems, and Power Electronic in Wind Turbines.

Section 8.1

Introduction

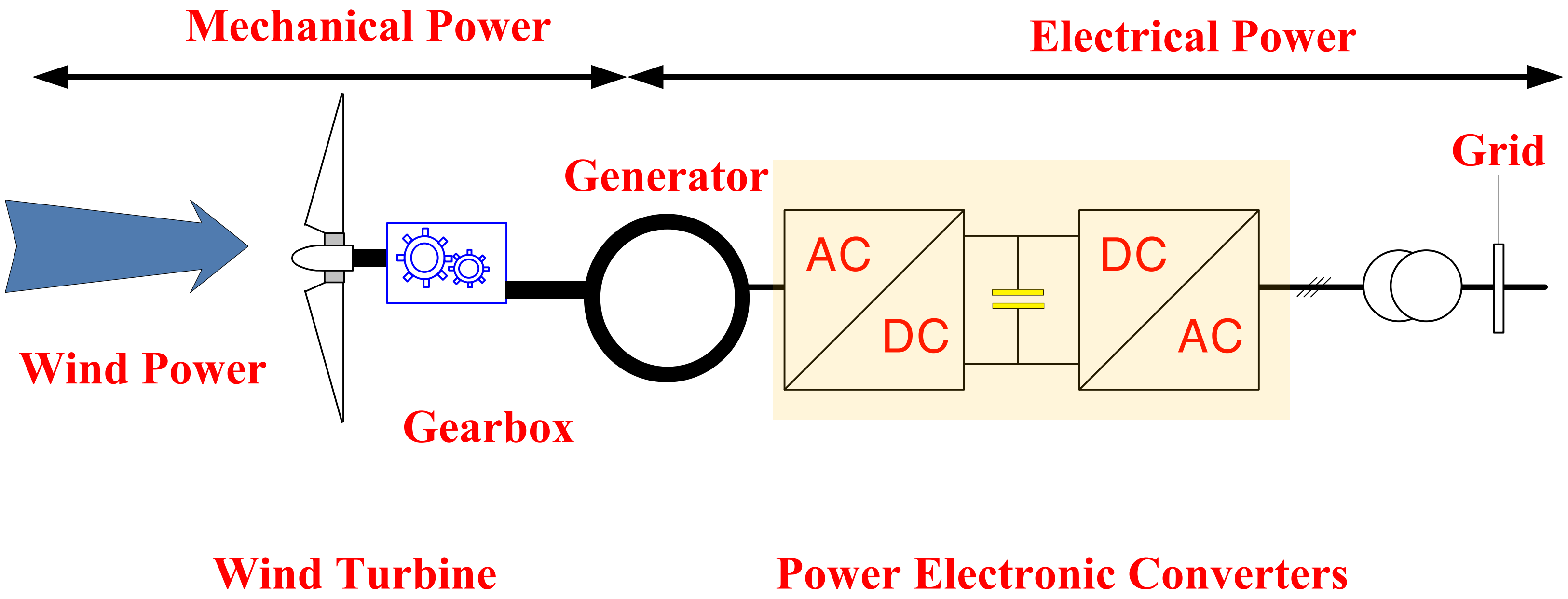
This week’s topics…

- Wind Turbines Components.
- Types of Wind Turbine Generators.
- Types of wind turbine generator systems.
- Power Electronic in Wind Turbines.

Introduction

Wind Turbines Components

- Wind turbines harvest wind power by aerodynamically engineered blades and transform it to rotating mechanical power.



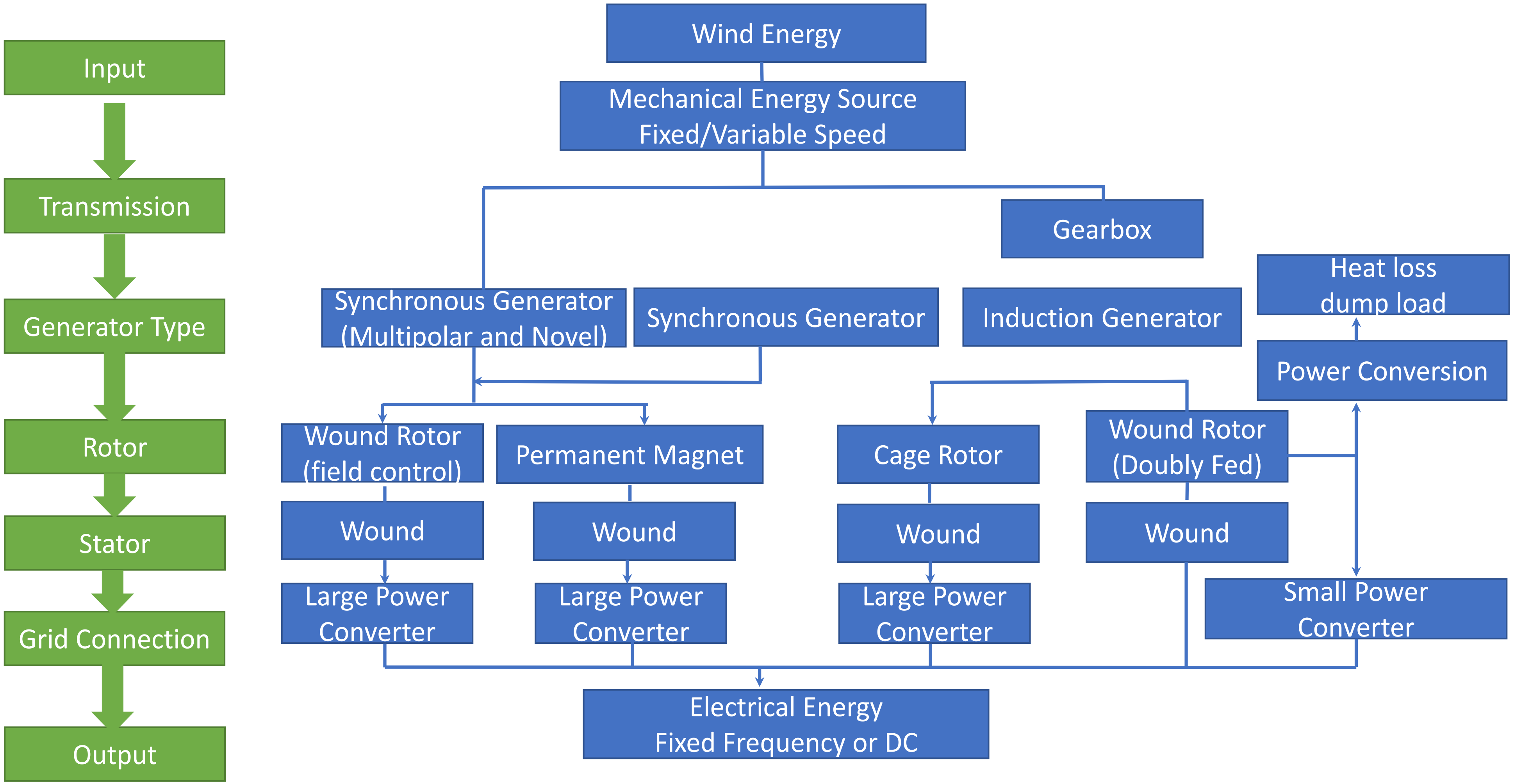
Introduction

Wind Turbines Components

- Wind Turbine : the number of blades is three. Since the tip-speed of the blade will usually be less than half the sound speed, the rotational speed should decrease as the blade radius increases
- Gearbox : to increase the rotational speed from a low-speed main shaft to a high-speed shaft connecting with an electrical generator
- Generator :Convert the mechanical power to electrical power
- Power Electronic converter: used for production, distribution, conversion, and efficient usage of electricity.

Introduction

Road-Map for Wind Energy Conversion



Types of Wind Turbine Generators

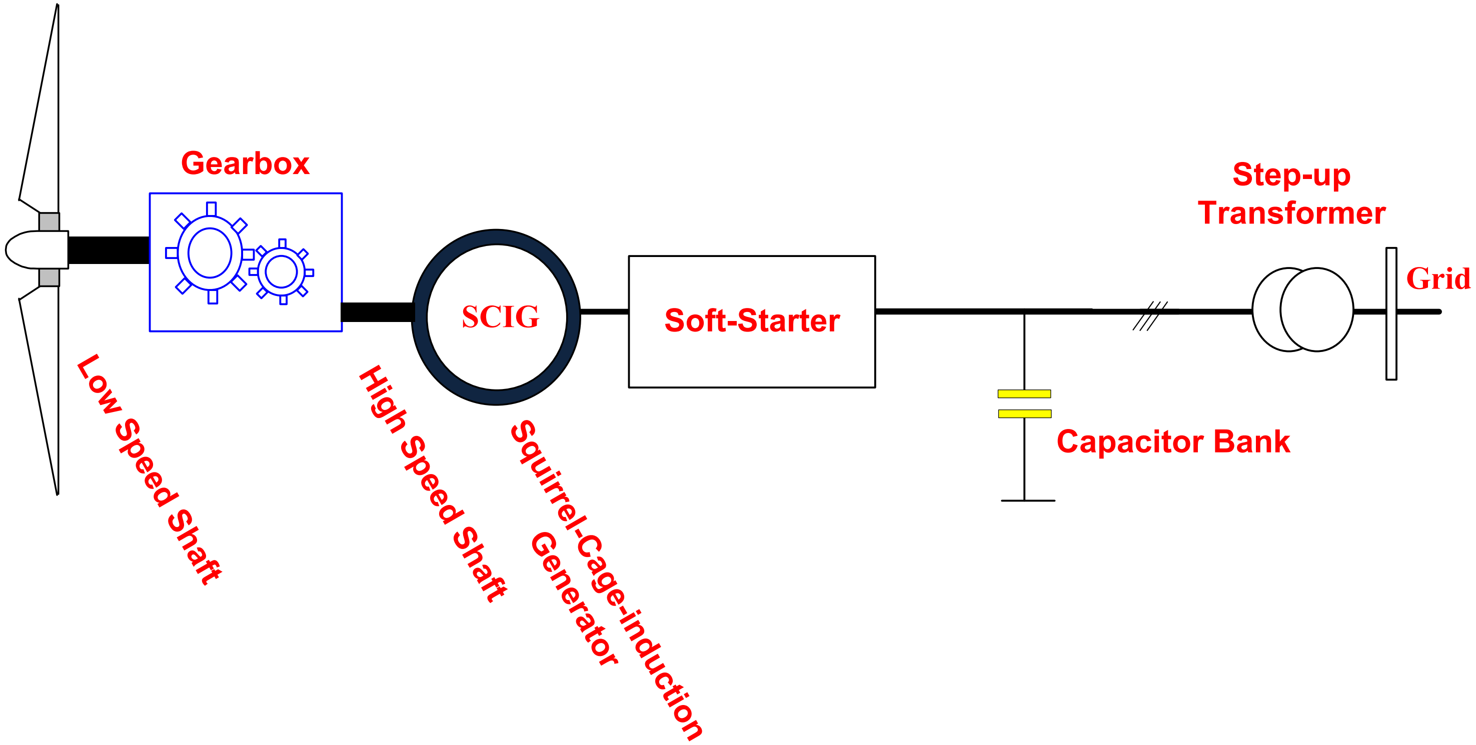
Introduction

- ○ In most wind turbines asynchronous (induction) and synchronous generators are used.
- ○ The typical generator used today in wind turbines is an induction generator, which also has different forms:
- Squirrel cage: (no access to the rotor winding) (the cheapest and the most durable machine)
- Wound rotor (slip ring): (access to its rotor windings by means of a configuration of brushes and slip rings).

Types of Wind Turbine Generators

Induction Generator : Squirrel-Cage

- The Squirrel-Cage Induction Generators
- Squirrel-cage induction generators are most widely used Type-1 wind turbine.



Types of Wind Turbine Generators

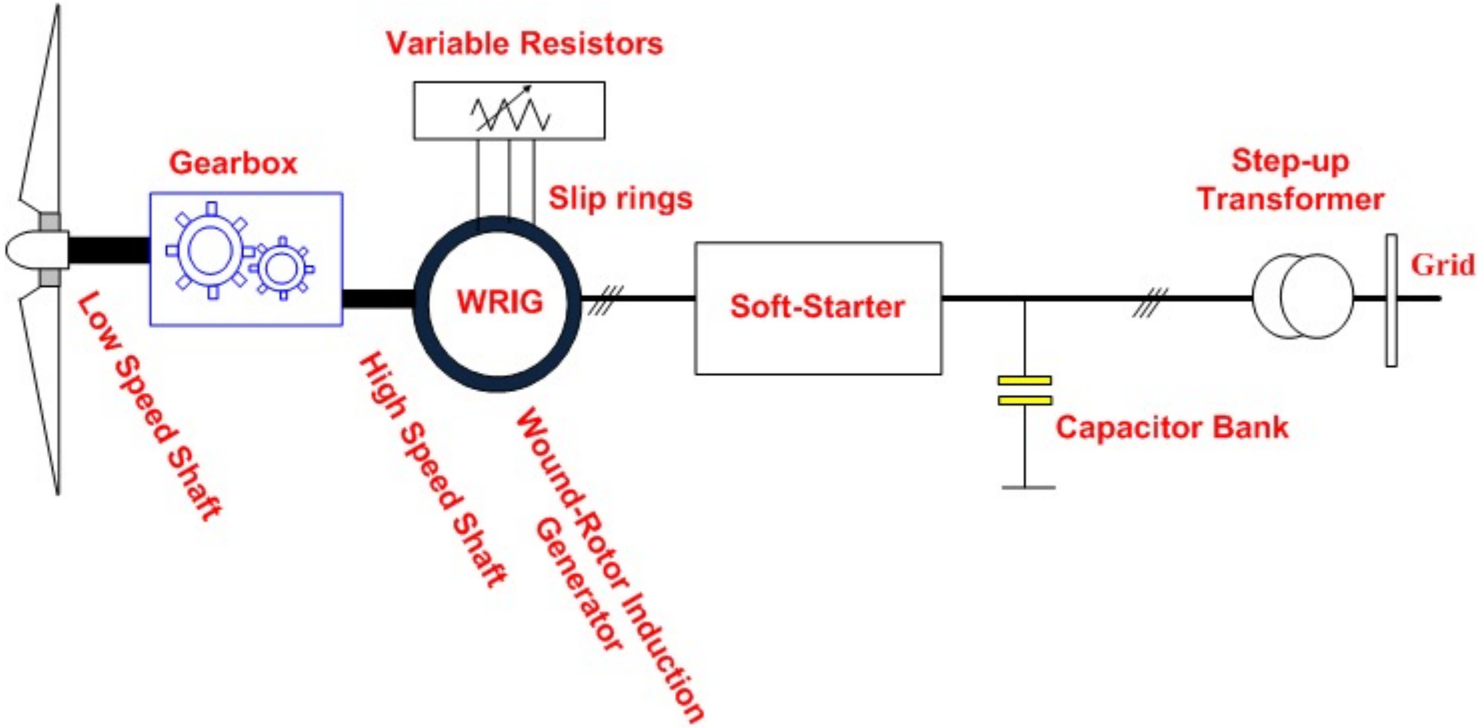
Induction Generator : Squirrel-Cage

- wired directly to the power grid (i.e. without a frequency-control power electronic converter).
- A gearbox is required to connect the low-speed shaft where the blades are connected to the high-speed shaft on the generator side.
- The induction generator rotates at almost synchronous speed (fixed-speed type).

Types of Wind Turbine Generators

Induction Generator: Wound-Rotor

- Wound-Rotor induction generators are most widely used Type-2 wind turbine.



Types of Wind Turbine Generators

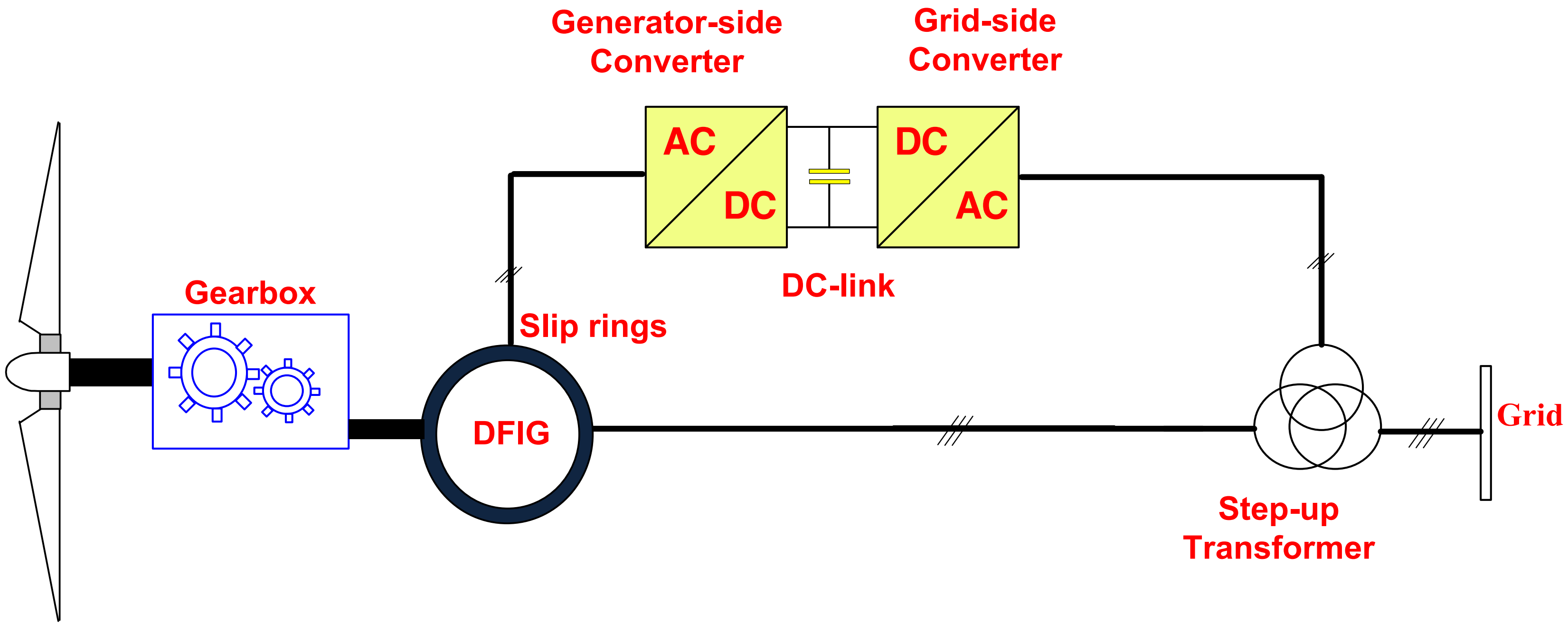
Induction Generator: Wound-Rotor

- The rotor windings are attached variable resistors, which can be operated from zero to maximum resistance per phase.
- To achieve system higher reliability, the control of resistor bank is achieved by an appropriate power electronic system.
- The control signals must be transmitted wirelessly to the rotor for external resistance adjustment.
- This will increase the heat is dissipated within the rotor which makes the machine design a challenging issue.

Types of Wind Turbine Generators

Induction Generator: Doubly-Fed Induction Generators (DIFGs)

- Doubly-Fed Induction Generators (DIFGs) are used Type-3 wind turbine.



Types of Wind Turbine Generators

Induction Generator: Doubly-Fed Induction Generators (DIFGs)

- Similar to the Type-2 turbine, this topology uses a wound-rotor induction generator.
- the key distinction is that the rotor of the doubly fed induction generator (DIFG) is simply connected to the power grid using a suitable power electronic converter.
- The most common power electronic converter used is a back-to-back ac-dc-ac converter, which comprises two different bi-directional converters attached with a dc link.

Types of Wind Turbine Generators

Induction Generator: Doubly-Fed Induction Generators (DIFGs)

○ The generator side converter has a dual role:

1. Controls the frequency of the currents in the windings of the rotor to maintain the synchronization of the magnetic fields between the stator and the rotor at all times.

2. Controls the amplitude and the phase shift of the currents in the windings of the rotor which ultimately means that both real and reactive powers provided to the power system are also controlled by such type of converters.

Types of Wind Turbine Generators

Induction Generator

- In General: The induction generator operates at a slip so its speed is not exactly constant. The machine itself without rotor injection cannot generate electricity unless it is rotating at higher than its synchronous speed n_s

$$n_s = 120\left(\frac{f}{p}\right)$$

where n_s is the synchronous speed, f is the frequency of the grid, p is the number of poles of the machine.

The slip of the machine s is defined as

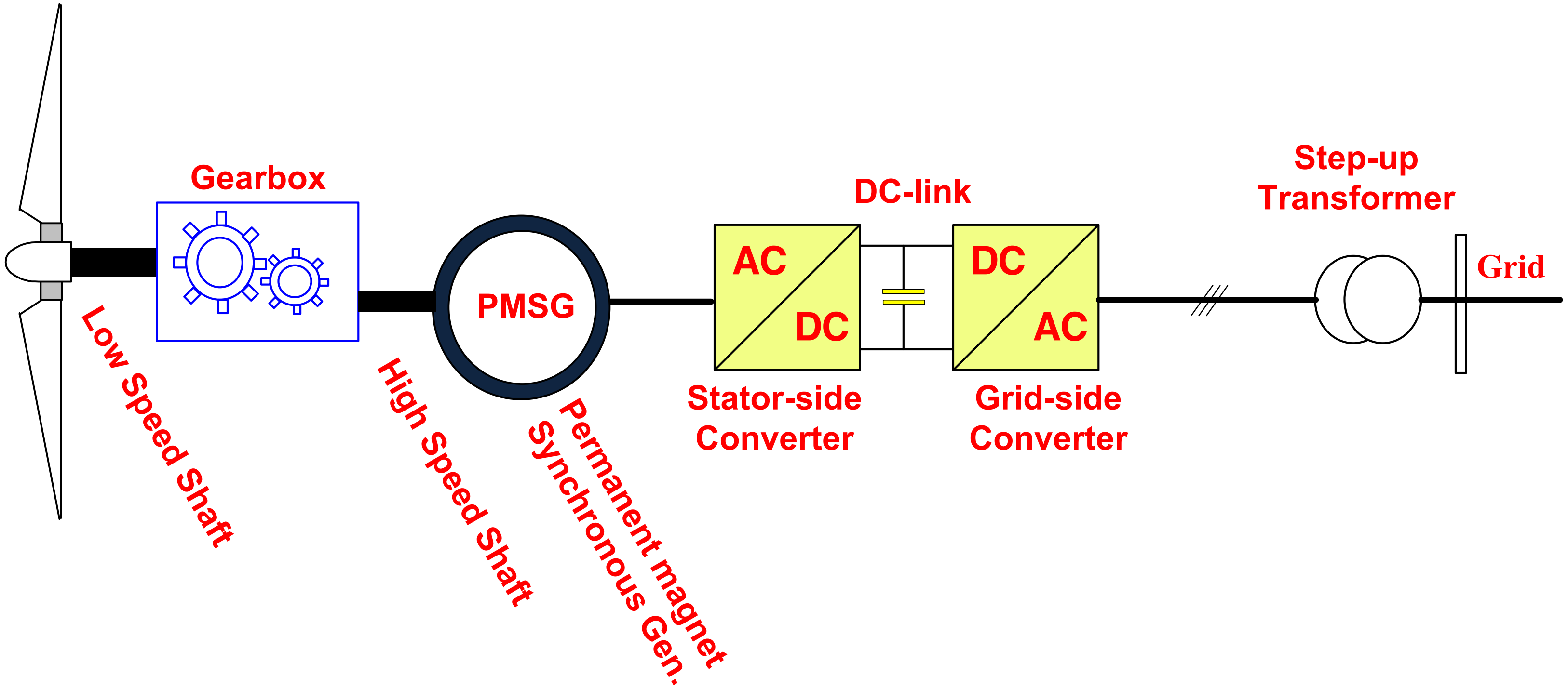
$$s = \left(\frac{n_s - n}{n_s}\right)$$

The slip of the induction generator, without rotor injection, is often small (2%–10%), and the generator needs to be a negative slip to generate electricity.

Types of Wind Turbine Generators

Permanent-Magnet Synchronous Generators

- The topology of Type-4 wind turbines which is based on permanent-magnet synchronous generators (PMSGs).



Types of Wind Turbine Generators

Permanent-Magnet Synchronous Generators

- In this configuration, a fully rated power electronics converter is used to interface the generator with the power system and hence handle the full power output of the generator.
- The converter allows the rotational speed of the system to be decoupled from the steady electrical frequency of the grid.
- In variable-speed operation, the stator-side converter produces ac voltages and currents of the required frequency to match the speed of the rotor because the rotor must synchronize with the stator's magnetic field in synchronous machines.

Types of Wind Turbine Generators

Permanent-Magnet Synchronous Generators

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Types of Wind Turbine Generators

Permanent-Magnet Synchronous Generators

- The converters can also control the generator's electromagnetic torque, by modifying the stator current's magnitude and phase. This allows the rotor speed to be changed in order to achieve the maximum tip-speed ratio.

Types of WT Generator Systems

Two types of wind turbine:

- Fixed-speed wind turbine (FSWT).
- Variable-speed wind turbine (VSWT).

Types of WT Generator Systems

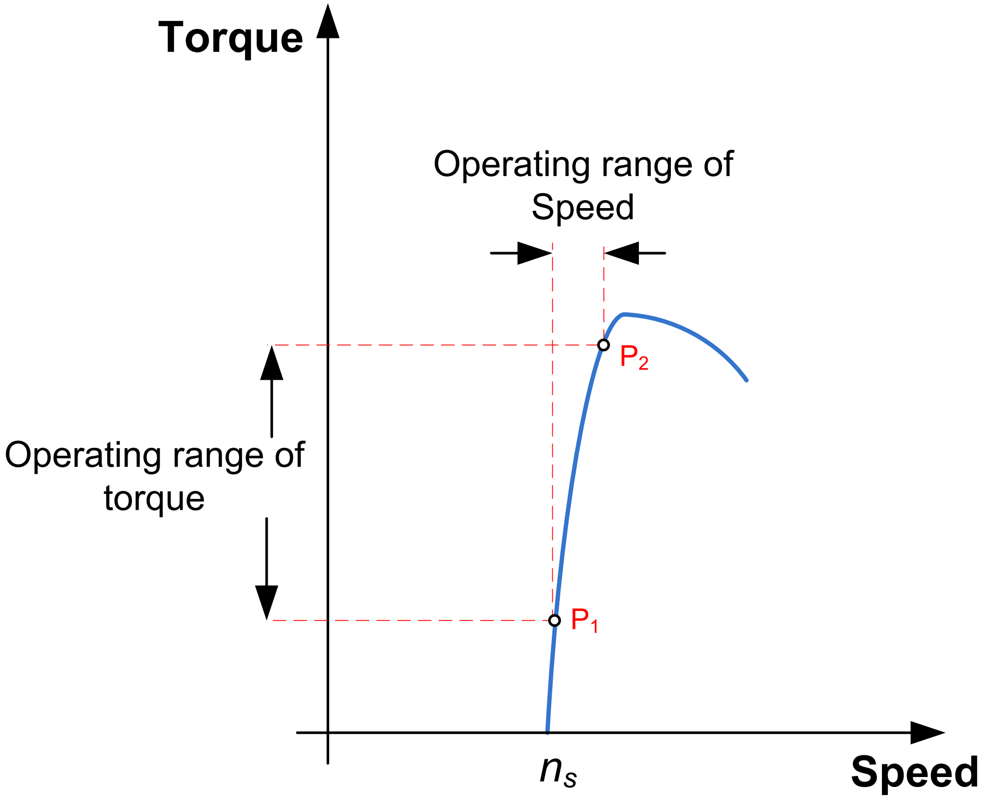
Fixed-Speed Wind Turbine (FSWT)

- Used in older model of wind turbine.
- Cheaper to construct and operate than variable-speed types.
- Requires less maintenance than the variable speed types.
- Electricity is generated only when the wind speed is high enough to rotate the generator shaft above its synchronous speed.
- Its power generation is limited.

Types of WT Generator Systems

Fixed-Speed Wind Turbine (FSWT)

- The torque-speed characteristic of the FSWT.



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Types of WT Generator Systems

Fixed-Speed Wind Turbine (FSWT)

○ The range of the developed power (shaft power of the generator) in this system can be given:

$$\Delta Pcs = P_2 - P_1 = T_2\omega_2 - T_1\omega_1$$

Where ΔP_{cs} is the range of the developed power of constant speed generator

P_1 is the developed power at point 1

P_2 is the developed power at point 2

T_1 is the developed torque at point 1

T_2 is the developed torque at point 2

ω_1 is the speed of the generator at point 1

ω_2 is the speed of the generator at point 2.

Types of WT Generator Systems

Fixed-speed wind turbine (FSWT)

- Finally, as $\omega_1 \cong \omega_2$, the equation can be rewritten as be.

$$\Delta Pcs = \mathrm{P}_2 - \mathrm{P}_1 = (\mathrm{T}_2 - \mathrm{T}_1)\omega_1$$

- The FSWT speed is relatively constant, the output power is controlled using the pitch angle control by changing the lifting force.

Types of WT Generator Systems

Variable-Speed Wind Turbine (VSWT)

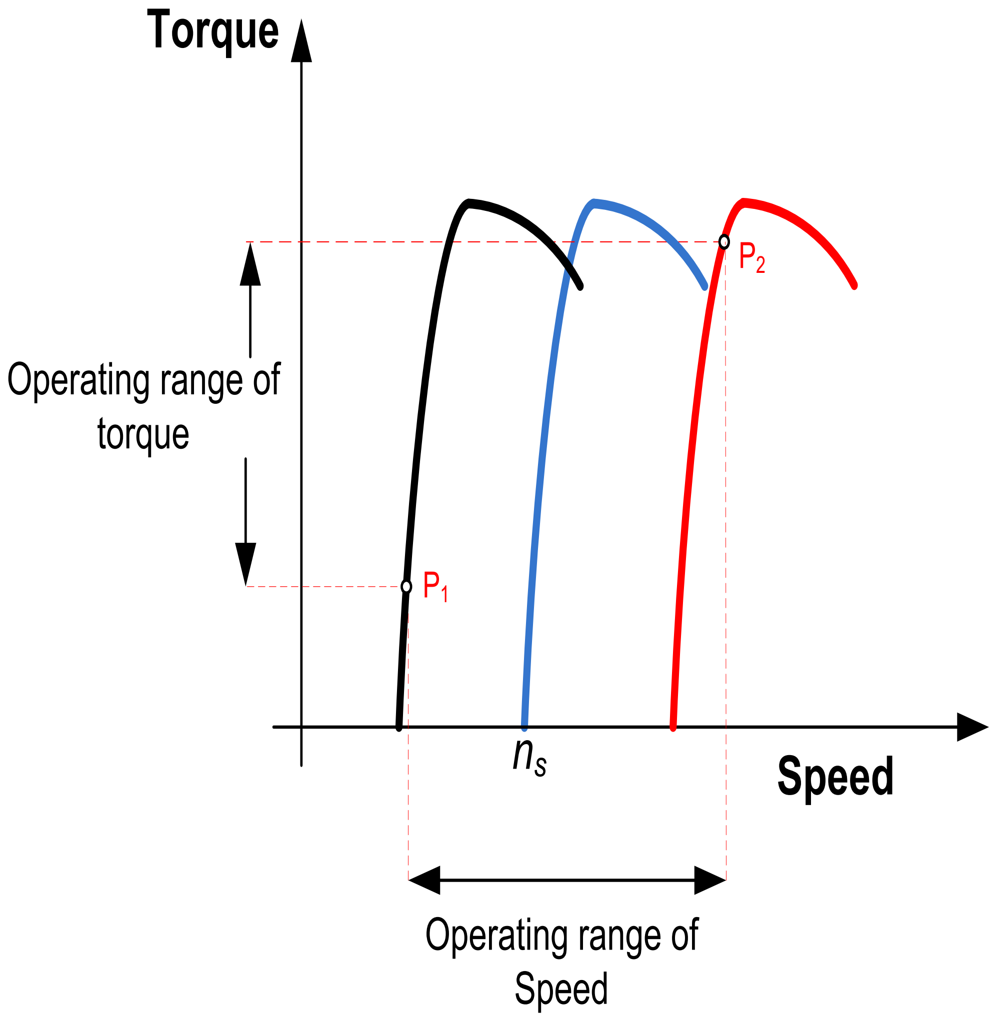
- VSWTs can generate electricity at a wide range of speeds even at less than synchronous speeds.
- Their range of operations is wider than the FSWT.
- Suffer from the increasing complexity of the system as power converters are required.

Types of WT Generator Systems

Variable-Speed Wind Turbine (VSWT)

- The torque-speed characteristics of the VSWT.

- A voltage is introduced into the rotor circuit of the generator to achieve these characteristics.



Types of WT Generator Systems

Variable-Speed Wind Turbine (VSWT)

- The speed of the generator is $P_2 > P_1$ when the operating torque is between T_1 and T_2. This machine has a range of power:

$$\Delta Pvs = \mathbf{T_2 \omega_2 - T_1 \omega_1}$$

- it can be concluded that the $\Delta P_{VS} > \Delta P_{CS}$ because the wider variation of operating speed.

Types of WT Generator Systems

Example:

- if the torque of a fixed speed generator is ranging from 500 NM to 3000 NM and its synchronous speed is 1200 rpm. Assume that the slip is −0.02, estimate the range of the established generator power.
- *Solution*
- the speed of the generator.

$$\boldsymbol{\omega_2 \cong \omega_1 = \omega_S(1 - s) = 128.18\, rad/s}$$

- The range of the developed power is

$$\boldsymbol{\Delta Pcs = P_2 - \ P_1 = T_2\omega_2 - T_1\omega_1 = 320.45\, kW}$$

Types of WT Generator Systems

Example:

- From the previous example, assume that the generator is equipped with a power converter which can operate the generator at a speed range of 900–1500 r/min. Estimate the range of the established power.
- *Solution*
- The range of the developed power is

$$\boldsymbol{\Delta Pvs = \mathrm{P}_2 - \mathrm{P}_1 = \mathrm{T}_2\omega_2 - \mathrm{T}_1\omega_2 = 424.12\ kW}$$

- It is an improvement in power range of about 32 per cent over the fixed-speed system.

Types of WT Generator Systems

Assessment of FSWT and VSWT

- For FSWT, the cut-in speed is higher than the synchronous speed of the VSWT generator.
- For FSWT, the rated power which is the power delivered by its stator windings is less than that for VSWT

Types of WT Generator Systems

Assessment of FSWT and VSWT

○ FSWT is still used for small size systems because of several reasons:

- No need for brushes or slip rings.
- Low maintenance.
- Rugged generator.
- Low cost.
- Simple to operate.

Types of WT Generator Systems

Assessment of FSWT and VSWT

○ The FSWT has many drawbacks, including:

- Wind speed variations result in continuous and abrupt tensional torques, which stress the drive shaft and gearbox, due to a fixed-speed operation.
- Rotation speeds are high, because they need to exceed the synchronous speed to produce power. For this to happen, the gear needs to be designed with high ratios or the blades needs to rotate at high speed.
- The FSWT can be very noisy and could cause more bird collisions because of its high speed.

Types of WT Generator Systems

Assessment of FSWT and VSWT

- The main advantages of VSWTs :
- Can generate power at low speeds (less than the synchronous speed)
- The output power can be controlled
- Generator speed can be adjusted so that aerodynamic efficiency is increased (Enhance the performance coefficient)
- Reduction of the torque of the drive train due to lower mechanical stress.
- noise and collision problems with bird are significantly minimized as the turbine rotates at low speed.

Types of WT Generator Systems

Assessment of FSWT and VSWT

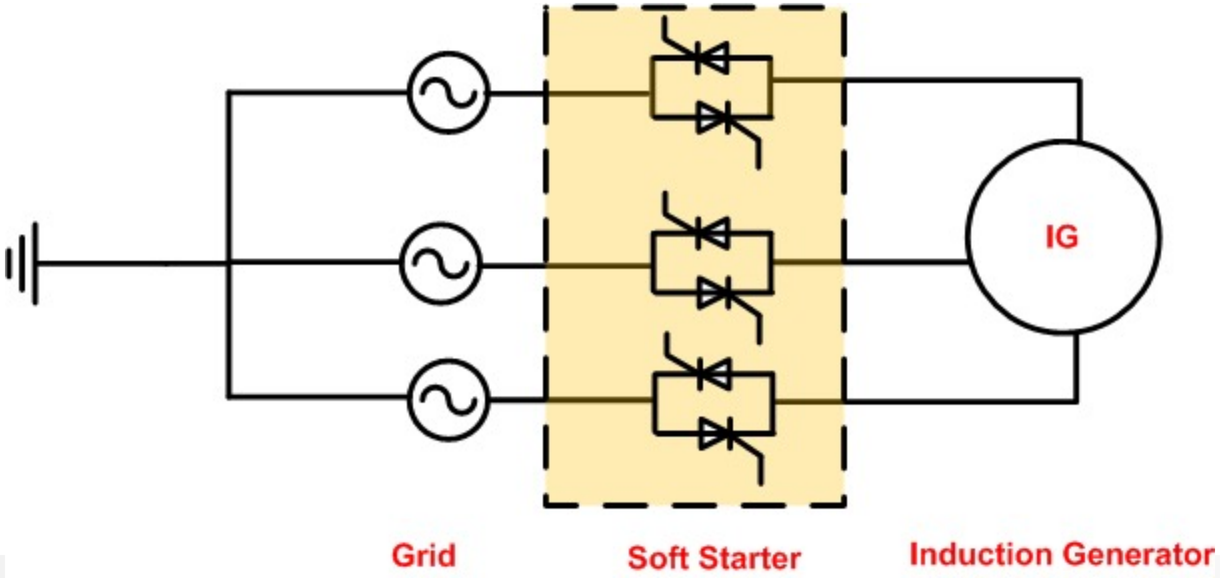
○ The VSWT's main disadvantages are:

- High costs
- More complex system (more system components)
- Increased maintenance costs

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 1

- **Soft-starter**
- The main function of the soft-starter is to reduce the inrush current (reduce the effects of the start-up situation) and thus prevent voltage/current disturbances in the grid



Power Electronic in Wind Turbines

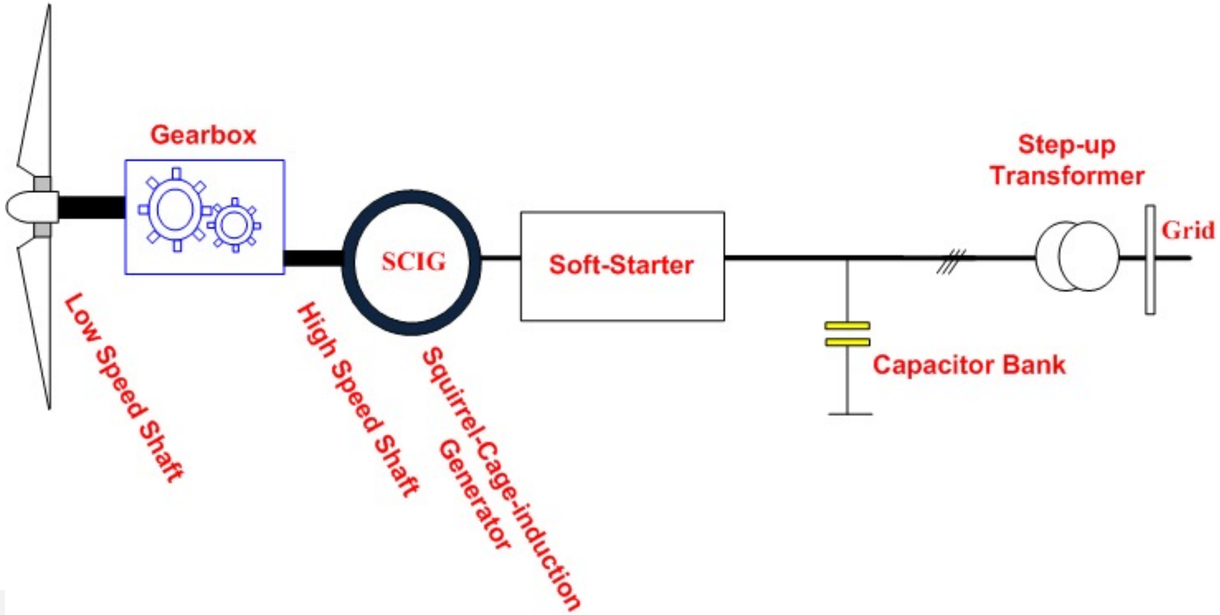
Power Electronics for Wind Turbine Type 1

- **Soft-starter**
- The smooth connection of the generator to the grid, during a predefined number of grid periods, is achieved by adjusting the firing angle of the thyristors.
- After the in-rush, the thyristors are bypassed in order to reduce the losses of the overall system.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 1

- **Capacitor bank**
- The capacitor bank is used in Types 1 and 2
- Used to supplies reactive power to the induction generator. Thus, the reactive power absorbed by the generator from the grid is minimized.



Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 2

- **Variable external rotor resistance**

The generated electrical power (P_e)

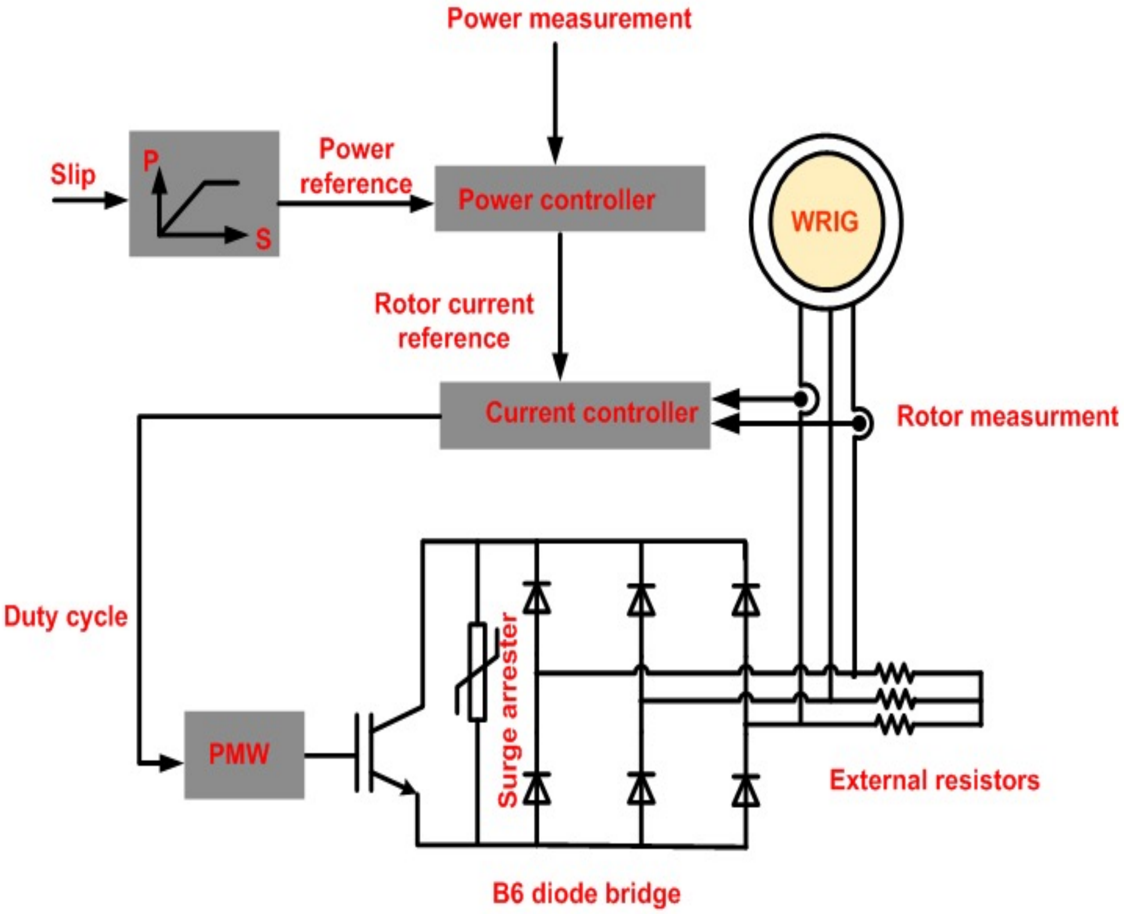
$$P_e = n_p I_2^2 \left(\frac{R_2}{s}\right) \cong n_p V_1^2 \left(\frac{s}{R_2}\right) \; for \; s \leq 0.02$$

where

n_p and V_1 are the number of phases and per phase terminal voltage of the stator windings.

I_2 and R_2 are the per phase rotor current and resistance referring to the stator side

s is the slip



Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 2

- If the speed of the rotor is increased above its synchronous speed, the generator starts to produce electrical power.
- When the wind speed increases above this point, the slip of the rotor increases hence the output power increases.
- If the generated electrical power has become below its rated value, then the external rotor resistors will be short circuited by making the duty ratio of the IGBT module to be 1

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 2

- when the generated output power reaches the rated value, the resistance of the external rotor is modified to maintain a constant output power

- This is accomplished by fixing the ratio of the overall rotor resistance to the slip to be constant as follows:

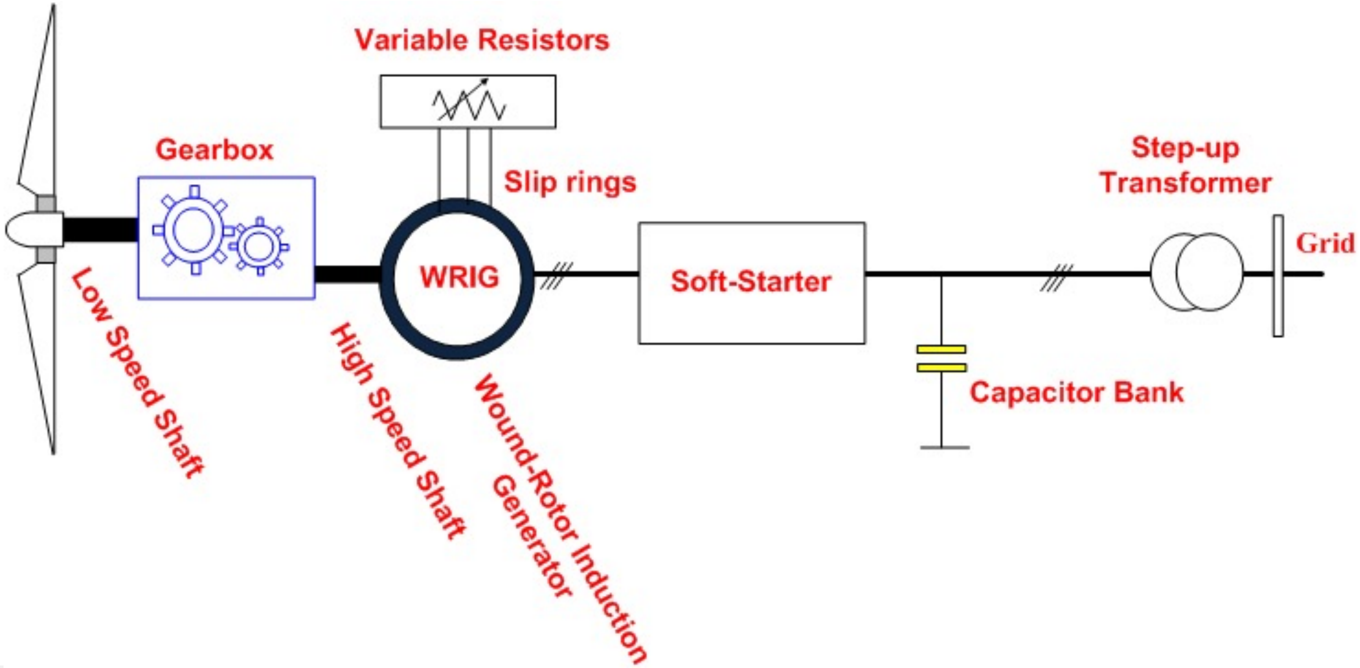
$$\frac{R_{2-\mathrm{Total}}}{s} = \frac{\mathrm{R}_2}{\mathrm{R}_{\mathrm{rated}}}$$

where: s_{rated} is the rated slip when the rotor resistance is R_2 ,R_{2_Total} is the sum of R_2 and the effective external rotor resistance.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 2

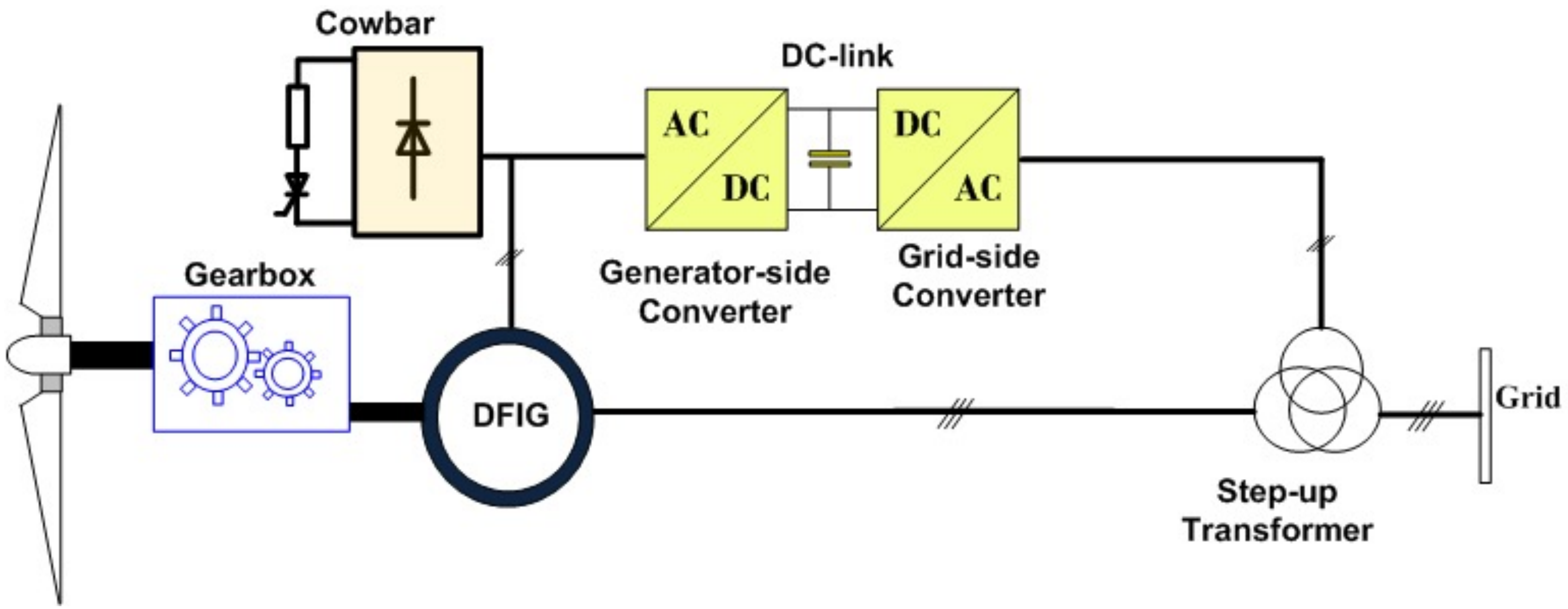
- The generators used in the type 2 wind turbine also need a soft starter to reduce the inrush currents during the start-up phase. In addition, they need switched capacitor banks to compensate for reactive power.



Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 3

- The basic configuration of a type 3 wind turbine generator



Power Electronic in Wind Turbines

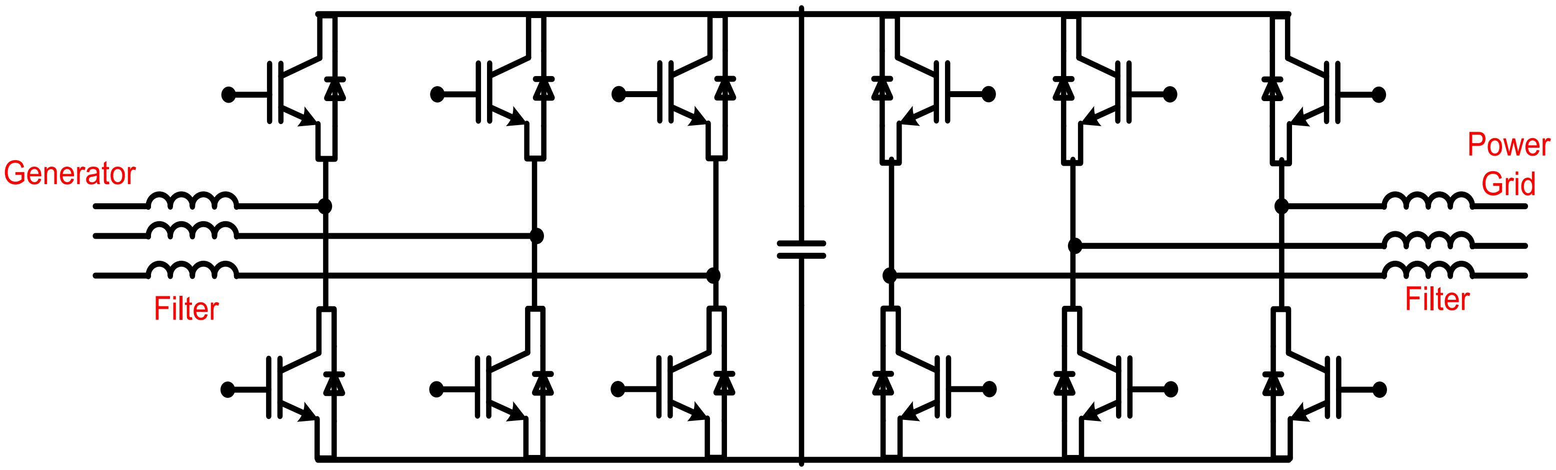
Power Electronics for Wind Turbine Type 3

- Variable-frequency AC – DC – AC converter
- The generator-side converter and the grid-side converter are generally rated at a fraction (approximately 30%) of the nominal generator power to carry the slip power.
- Forced-commutated converters typically used in type 3 wind turbine generators, such as IGBT-based pulse width modulated (PWM) VSCs.
- This type of power converters has the ability to control both the active and reactive power delivered to the grid.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 3

- Variable-frequency AC – DC – AC converter
- Topology of back-to-back PWM-VSCs used in wind power systems



Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 3

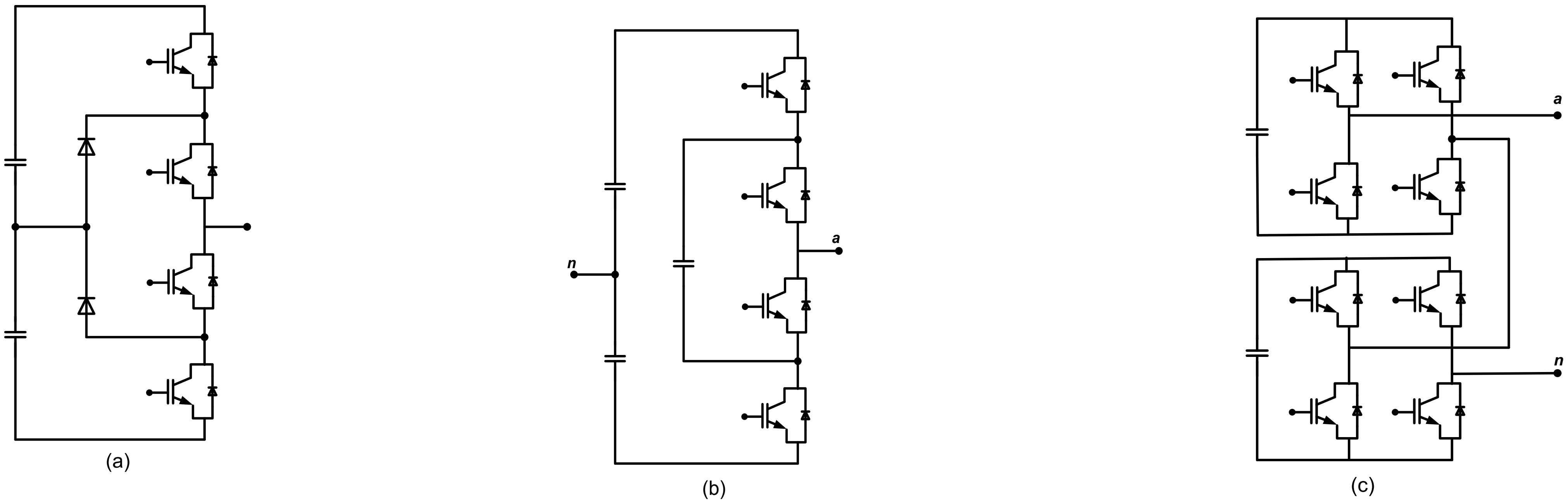
○ The widely used topologies for multi-level converters can be divided into three categories:

- Diode clamped multi-level converters.
- Capacitor clamped multi-level converters.
- Cascaded multi-level converters.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 3

- Multilevel converter topologies;

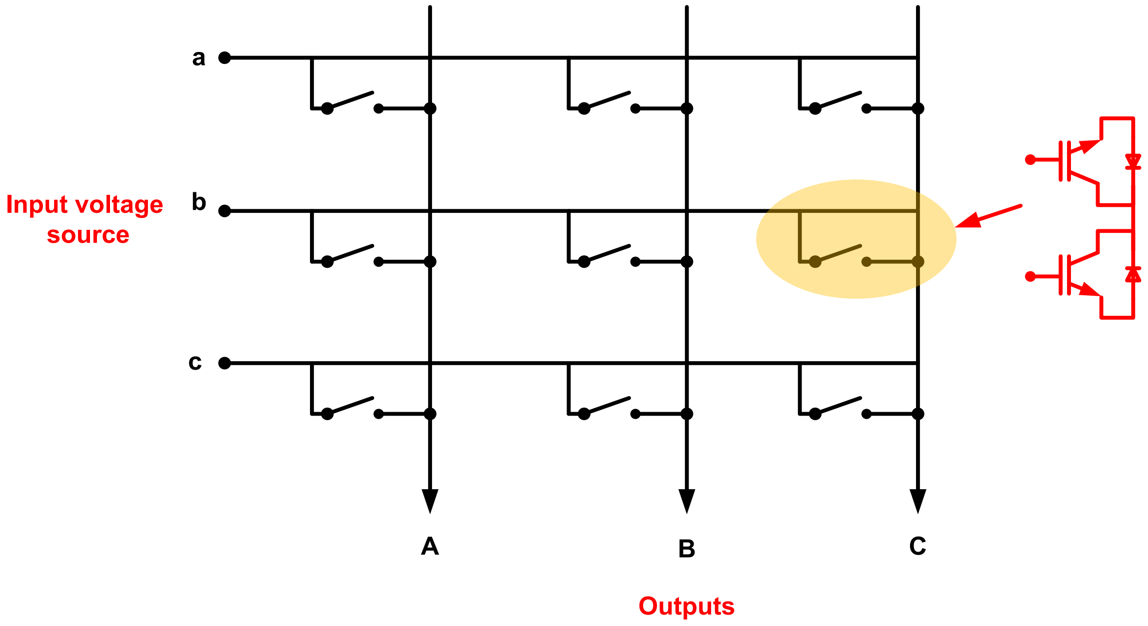


(a) one leg of a diode clamped 3 -level converter; (b) one leg of a capacitor-clamped 3 - level converter; and (c) one leg of an H-bridge cascaded 3 - level converter.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 3

- ○ The matrix converter;
- ○ The following two control rules must be complied with in order to protect the converter.
- ○ Only 1 switch inside the output leg of the matrix converter can be turned on at any given time.
- ○ All 3 output phases (A, B, and C) have to be linked to a specific input phase at any point of time.

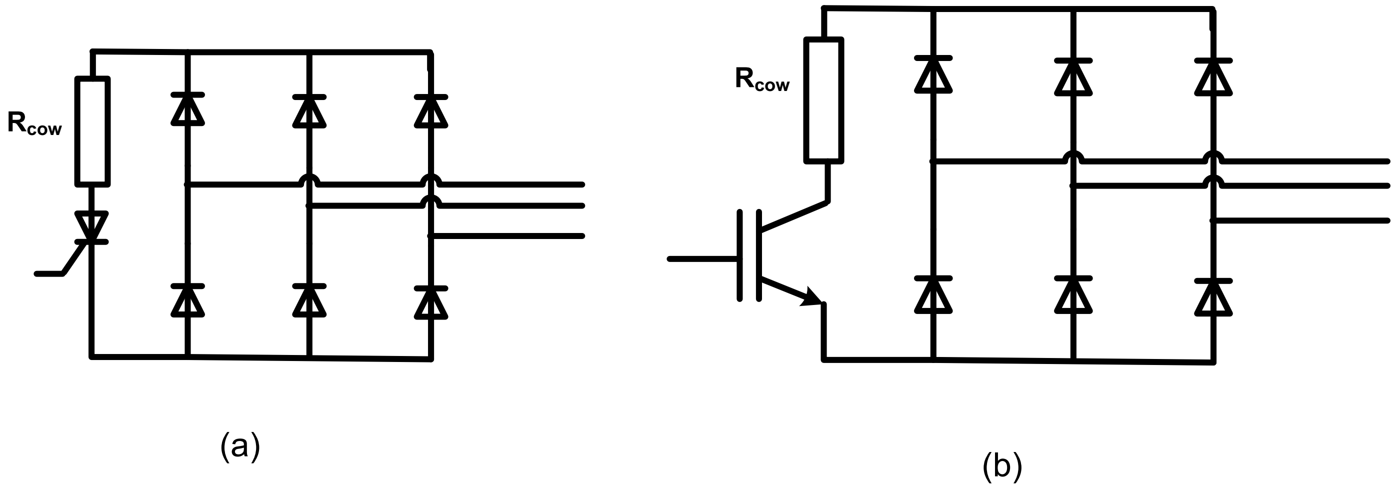


Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 4

- Crowbar circuits:
- Crowbar circuit is typically connected between the DFIG rotor circuit and the generator side converter to short-circuit the rotor windings if a grid fault is happened

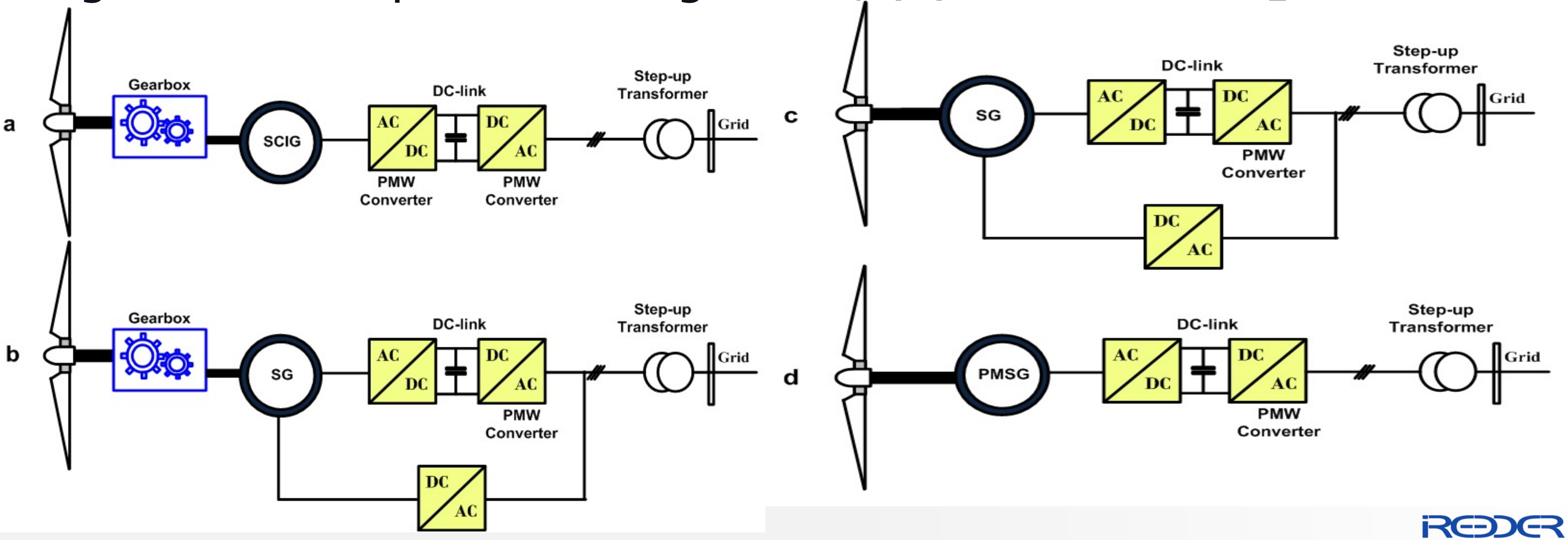
- (a) Passive crowbar
- (b) Active crowbar



Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 4

- Configurations of wind turbine type 4 equipped with: (a) SCIG and gearbox; (b) wound-rotor SG and gearbox; (c) wound-rotor SG with a high number of poles but no gearbox; (d) PMSG but no gearbox.



Power Electronic in Wind Turbines

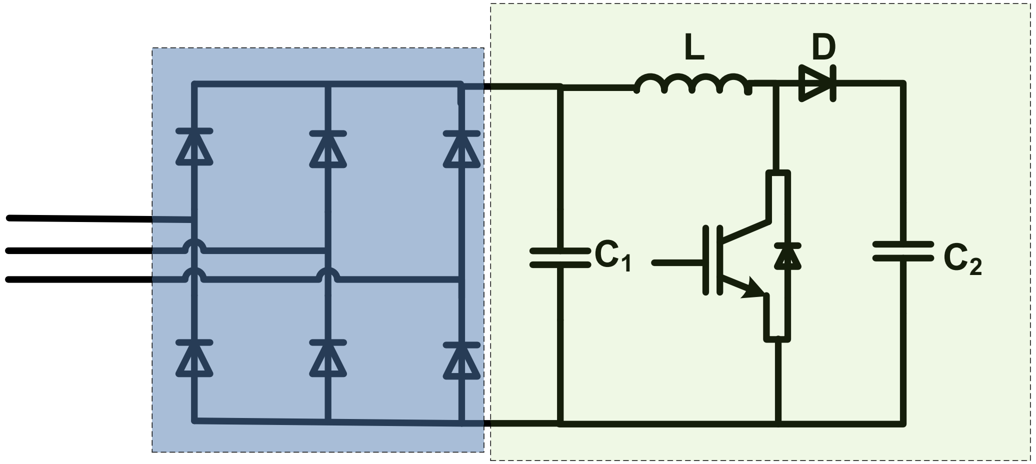
Power Electronics for Wind Turbine Type 4

- The AC –DC –AC converters can be can be utilized to obtain full control over the active and reactive power of the generators through the bidirectional back to back PWM VSC.
- The WRSG and PMSG types require only a basic bridge rectifier in the generator side converter. For a three-phase network, the required rectifier requires only 6 diodes.

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 4

- For variable-speed operation, the wind turbine with a SG need to be equipped with a boost DC–DC converter which inserted between the diode rectifier and the DC link.



Diode Rectifier

Boost DC-DC Converter

Power Electronic in Wind Turbines

Power Electronics for Wind Turbine Type 4

- The type 4 wind turbines with a PMSG are the most popular configuration of small wind turbines where the grid-side converter could be a single-phase full bridge.
- A matrix converter can be used to replace the AC –DC –AC converter for wind turbine systems of type 4.

Thank You

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Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Introduction to Renewable Energy

Lecture 9: Wind Turbines operation and Control (2/2)

Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

Co-funded by the
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Section Outline

In this section, wind resource and wind forecasting are discussed. Wind turbine monitoring systems are presented, the balance of plant is explained and standards and technical specifications for wind turbines are described.

Section 1

Wind Turbines operation and Control (2/2)

This week's topics…

- Wind resource
- Wind forecasting
- Monitoring systems
- Balance of plant
- Standards and technical specifications

Wind resource

- Wind is formed by pressure differences in the surface due to uneven heating by the Sun
- Equator absorbs more energy than the poles
- Convective cells are formed in the troposphere, air rises from equator and sinks in the cooler poles
- Air moves from high pressure to low pressure areas, wind appears mainly in the horizontal plane
- Air circulation is affected by Earth's rotation, seasonal variations in solar energy, air's inertia, friction that causes turbulence

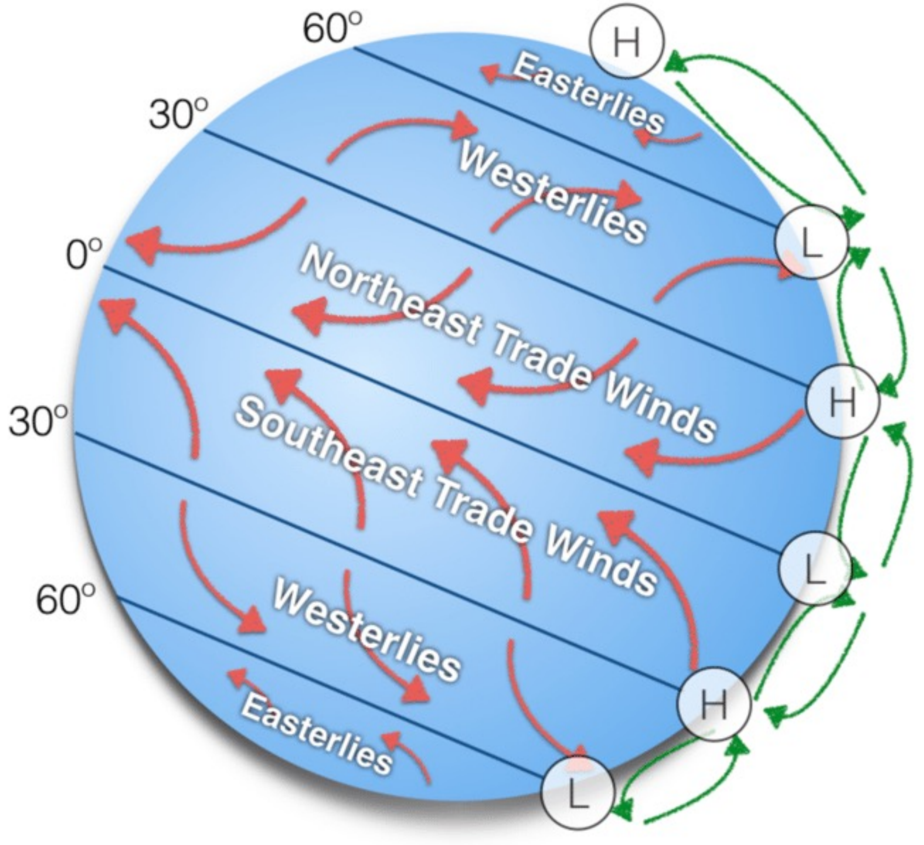


Figure 9-1: Horizontal surface wind circulation patterns.

Wind resource

- Inter-annual wind variations are changes in wind speed in time periods greater than a year
- They are important when calculating long term wind production. Study of wind data for the last 2-3 decades
- Annual variations include changes in seasonal & monthly wind speeds
- Very common in most locations in world
- Annual variations differ depending on location

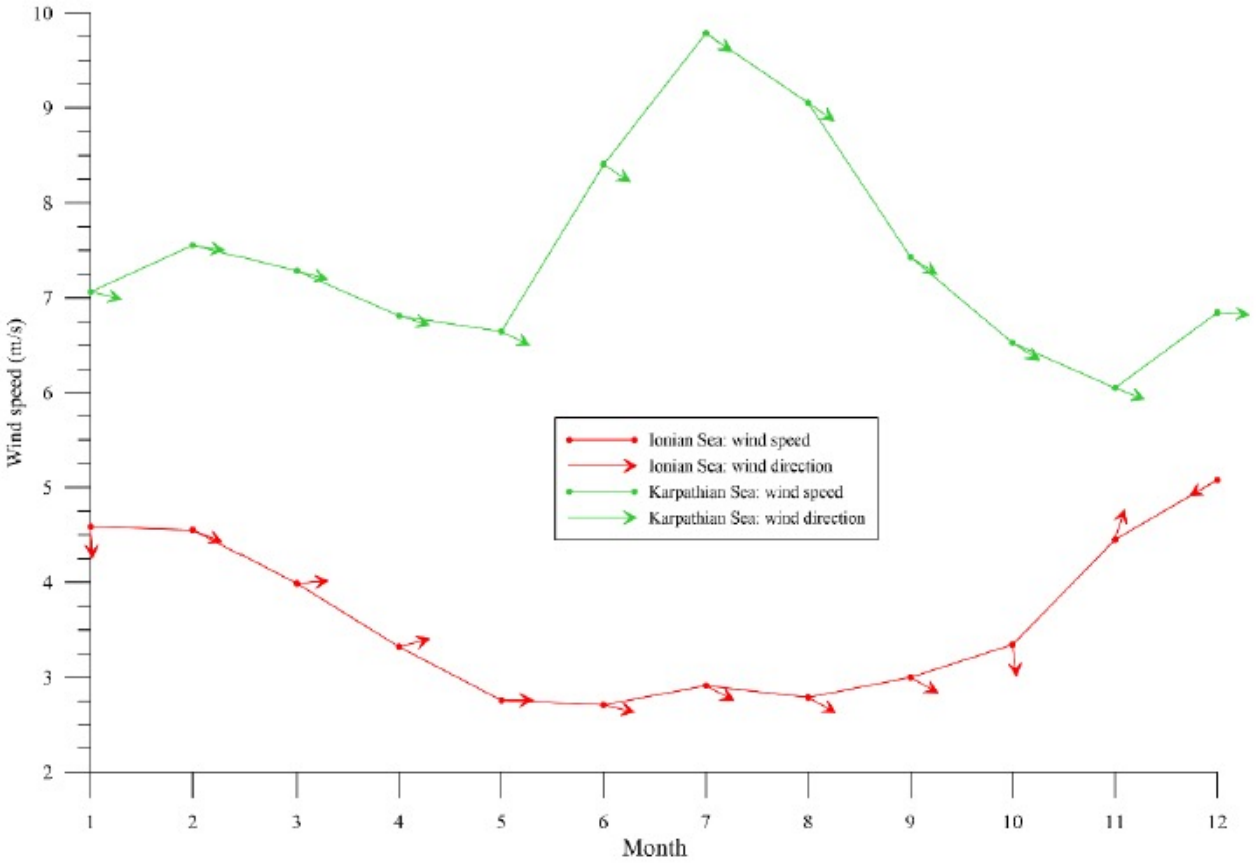


Figure 9-2: Seasonal variations of wind speed and wind direction in locations of the Aegean and Ionian Seas.

Wind resource

- Diurnal variations occur during one day, caused by difference in surface heating by the Sun throughout the day
- Typically wind speed increases during day and decreases in Sun absence
- Short-term variations occur when wind speed changes within minutes
- Turbulence involves variations in time intervals of less than 1 second up to 10 minutes, stochastic nature

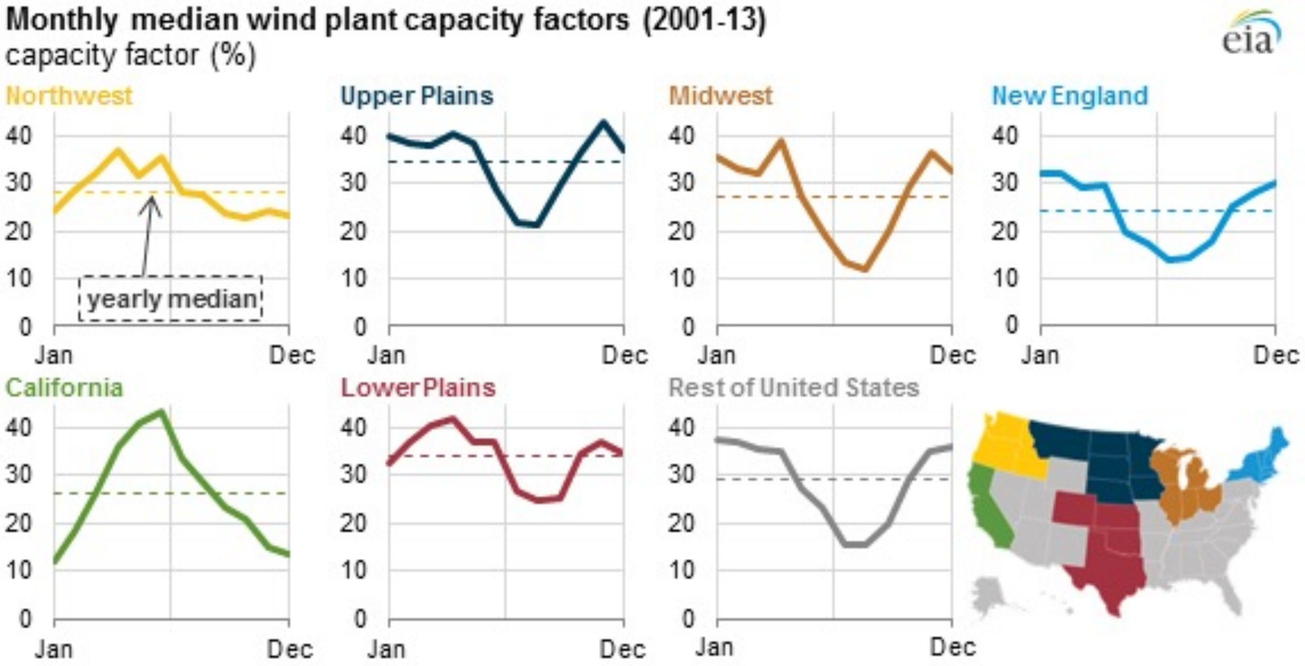
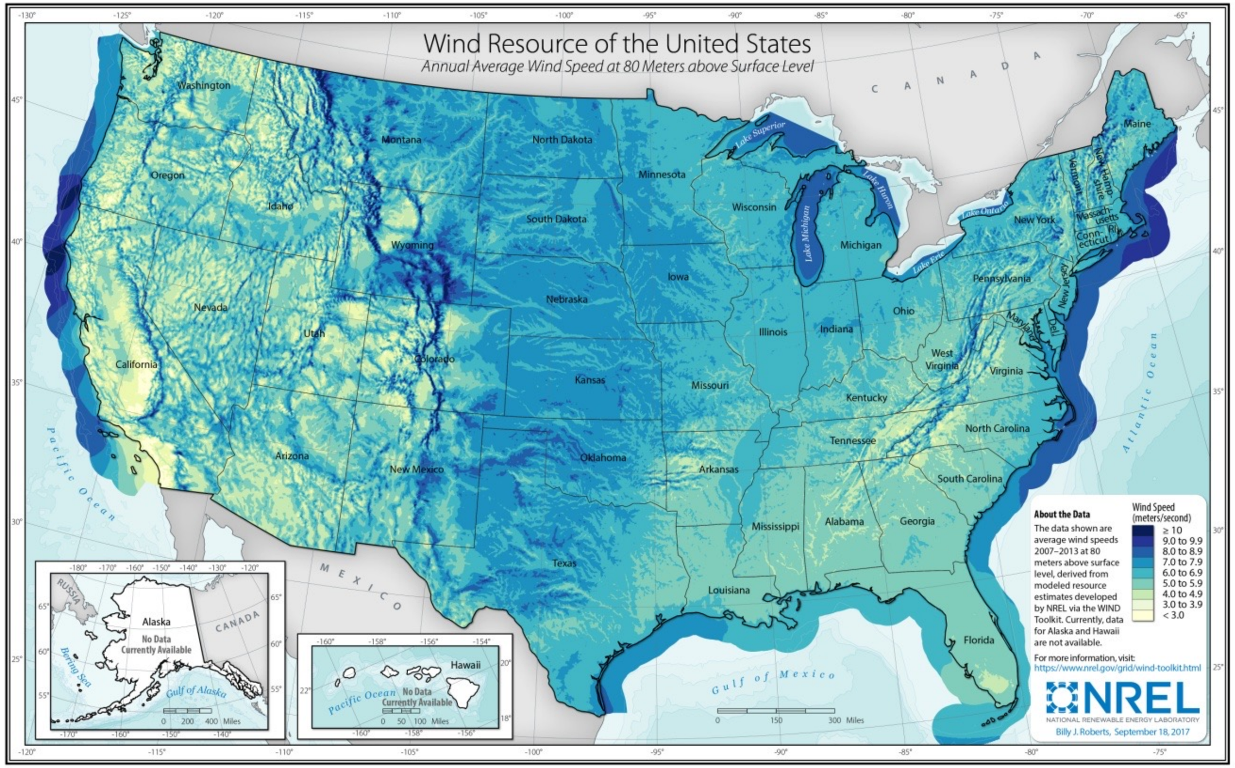


Figure 9-3: Monthly median wind plant capacity factors, for 2001-2013.

Wind resource

- Gust occurs within a turbulent field, described by amplitude, rise time, maximum gust variation, lapse time
- Wind speed presents spatial variations due to different topographical and surface characteristics of each location
- Wind direction also changes in same time scales as wind speed
- These changes affect the rotation of wind turbines and thus available wind power



About the Data

The data shown are average wind speeds 2007–2013 at 80 meters above surface level, derived from modeled resource estimates developed by NREL via the WIND Toolkit. Currently, data for Alaska and Hawaii are not available.

For more information, visit: https://www.nrel.gov/grid/wind-toolkit.html

Figure 9-4: Annual average wind speed at 80m above surface level in the USA.

Wind resource

Wind resource estimations

- Mass flow rate of air is a function of area A through which air flows, air density ρ and wind speed u:

$$\frac{dm}{dt} = \rho * A * u$$

- Kinetic energy per unit time (power P) of air flowing through surface A:

$$P = \frac{1}{2} * \frac{dm}{dt} * u^2 = \frac{1}{2} * \rho * A * u^3$$

- Wind power density:

$$\frac{P}{A} = \frac{1}{2} * \rho * u^3$$

Wind resource

Wind resource estimations

- ○ Wind power is proportional to third power of wind speed
- ○ Annual average wind speeds can provide wind power density maps for area
- ○ Based on wind speed data and efficiency of wind turbines, maps of wind power density potential can be produces for regions/countries
- ○ Maps give a first indication of suitable locations for wind power installations
- ○ Wind resource assessment can also be derived from measurements, modeling

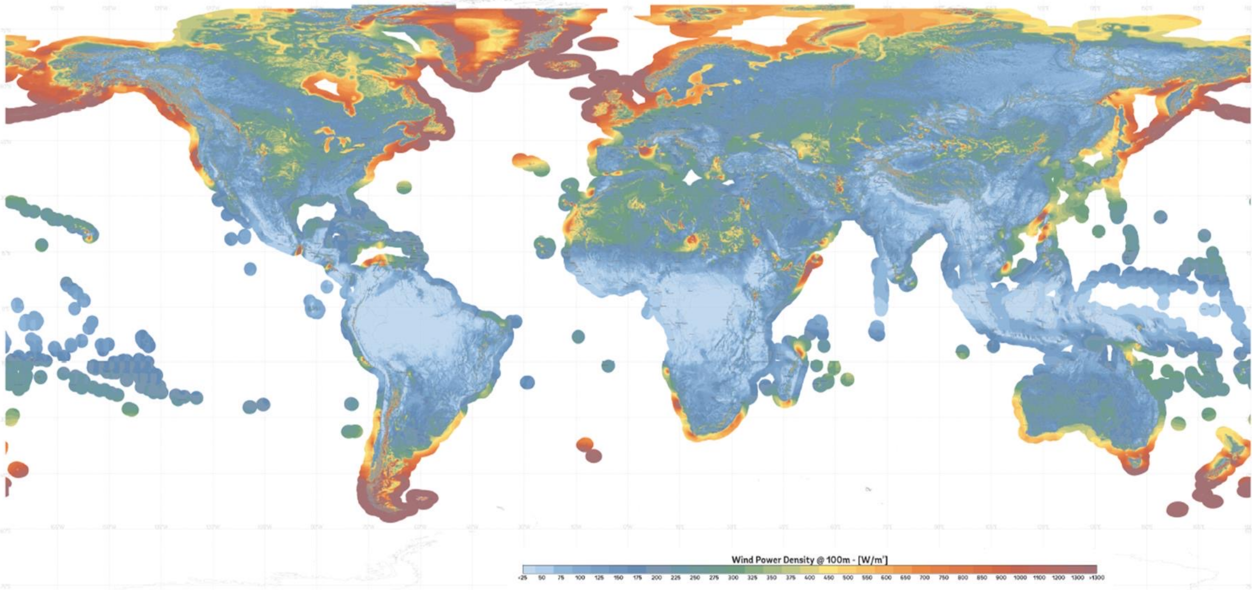


Figure 9-5: Wind power density potential.

Wind resource

Wind forecasting

- Wind power generation depends on wind availability, forecasting is important to integration of wind power to grid
- Wind power forecasting has various methods, for various time-scales
- Ultra-short-term forecasting: from few minutes up to one hour ahead
- Short-term forecasting: one hour to several hours ahead
- Medium-term forecasting: several hours up to one week ahead
- Long-term forecasting: one week up to several months ahead or longer

Wind resource

Wind forecasting

- Persistence method: wind speed or power at a certain time in the future is assumed to be the same as speed/power in present time
- Measuring wind speed and calculating power will provide data for desired future time
- This method is accurate for ultra-short-term forecasting and degrades as forecast time horizon increases
- Simplest forecasting method with lowest cost

Wind resource

Wind forecasting

- Physical methods use parameterizations based on detailed atmospheric physical description with the purpose of converting wind to power
- Physical approach includes various models describing different physical processes, like wind conditions, shading effects, turbine power curve etc.
- Numerical Weather Prediction (NWP) models provide weather forecasts used as input in physical wind power forecast models

Wind resource

Wind forecasting

- Meteorological measurements, observations, satellite data, used as input in NWP model, which calculates future state of atmosphere from physical laws
- NWP run on supercomputers once or twice a day
- This forecast is useful for medium to long-term forecasts
- Statistical methods make use of previous wind data to perform forecast for next few hours
- They use difference between predicted and measured wind speed in immediate past to adjust model parameters and make future predictions

Wind resource

Wind forecasting

- Statistical methods are easy to model, inexpensive approach, suitable for short-term forecasts
- They include time-series based models and neural network (NN)
- Time-series based models include Auto-Regressive Moving Average (ARMA) and Auto-Regressive Integrated Moving Average (ARIMA)
- NNs use past data from long time periods, for training in the relationships between input and output data. They include input, hidden and output layer

Wind resource

Wind forecasting

- Hybrid forecasting methods: physical with statistical approaches or short-term and medium-term models, improve prediction accuracy
- Error in wind speed forecast will give much larger error in wind power forecast
- Various types of turbines (various wind speeds and directions) increase complication in the forecasting process

WT monitoring systems

- Maintenance an important part in wind turbine overall cost, various strategies
- Corrective maintenance is implemented after component failure
- Preventive maintenance can be pre-determined or condition-based
- Pre-determined or time-based refers to maintenance in fixed time intervals. May not catch failure in its beginning
- Condition-based maintenance (CBM) or predictive, is based on data collected by condition monitoring systems (CMS)

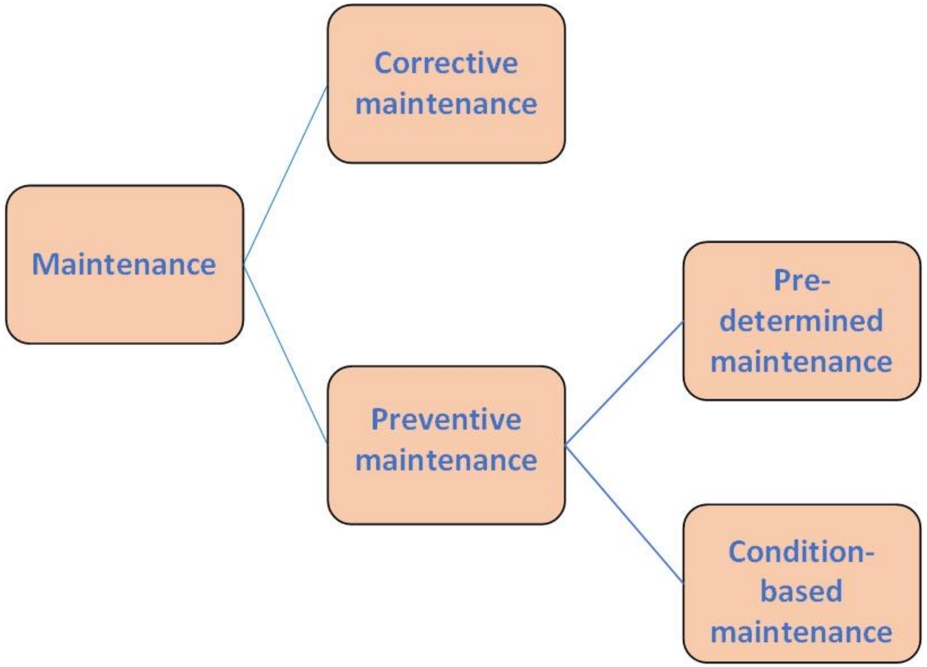


Figure 9-6: The maintenance strategies based on the European Standard EN 13306.

WT monitoring systems

- CMS can give information of turbine components condition and detect developing failure, using condition monitoring (CM) techniques
- CM can be done offline (regular measurements and inspections) or online (installation of monitoring equipment)
- CM can be used for most of turbine components
- Monitoring of structural components (support structures, blades) is called structural health monitoring (SHM)

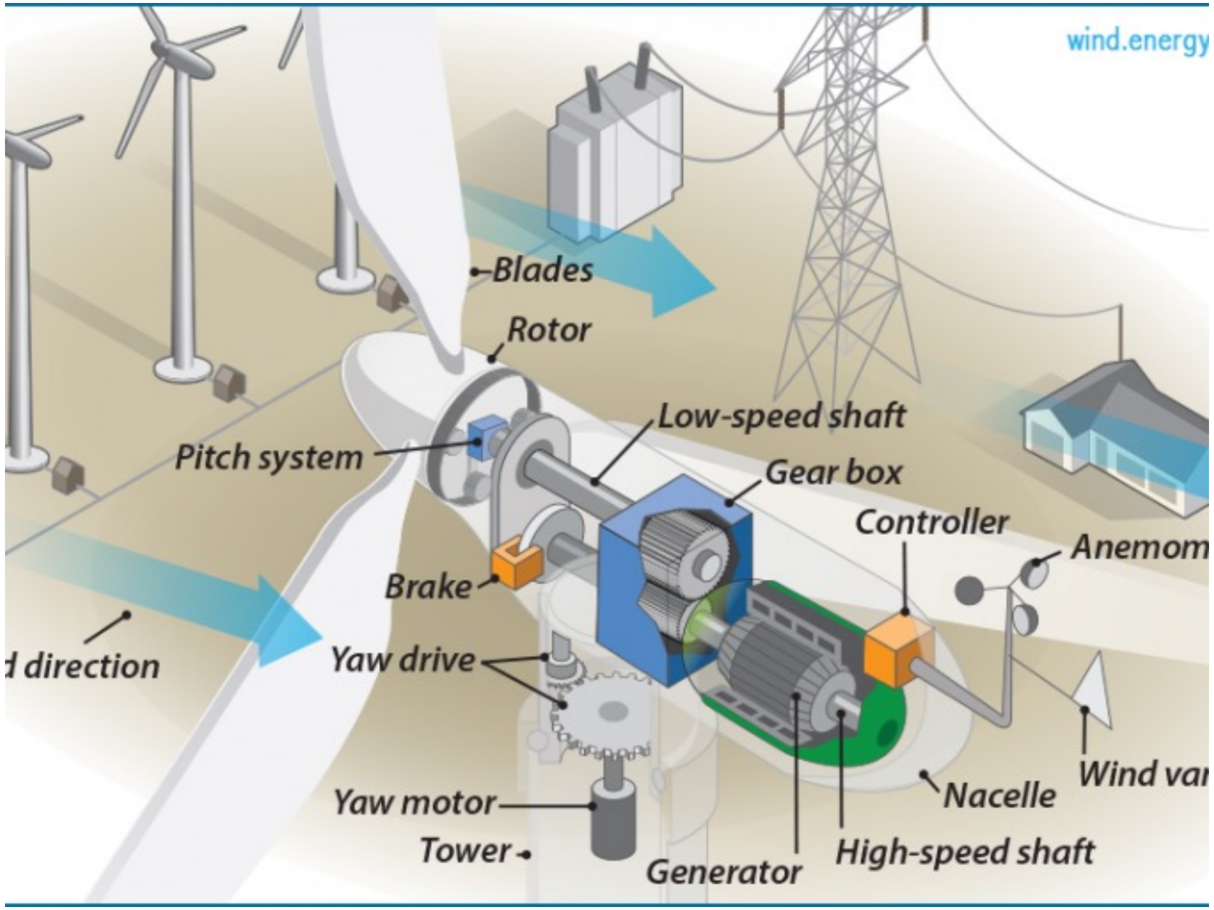


Figure 9-7: Main components of a wind turbine.

WT monitoring systems

Monitoring techniques

- Commercial CMS for wind turbines are usually vibration-based systems
- They monitor the rotating drivetrain components, which include main bearing, gearbox, generator bearings, tower oscillations
- Vibration-based CMS is standard equipment but as turbines grow larger and locations more remote, further component monitoring is required
- Other commercial monitoring systems are particle-counting systems for gearbox oil and SHM systems for rotor blades and support structures

WT monitoring systems

Monitoring techniques

Vibration analysis

- Vibration-based monitoring systems rely on fact that most failures of rotating components result in vibration effects that can be detected
- Depending on mechanical component, different vibration pattern emerges
- Time waveform of vibration signal is decomposed to spectral components and characteristic frequencies produced in resulting spectrum are associated with corresponding faulty component
- Sensors used in vibration-based CMS are position transducers, velocity sensors, accelerometers and spectral emission sensors (low, middle, high and very high frequency rages, respectively)

WT monitoring systems

Monitoring techniques

Vibration analysis

- Signal can be processed with various methods, which can be time-domain or frequency-domain analysis methods
- Time-domain analysis methods include statistical methods and time-synchronous averaging
- Frequency-domain analysis methods include Fast-Fourier Transform and spectrum analysis
- Vibration analysis can be applied to turbine components such as gearboxes, bearings, shafts and blades

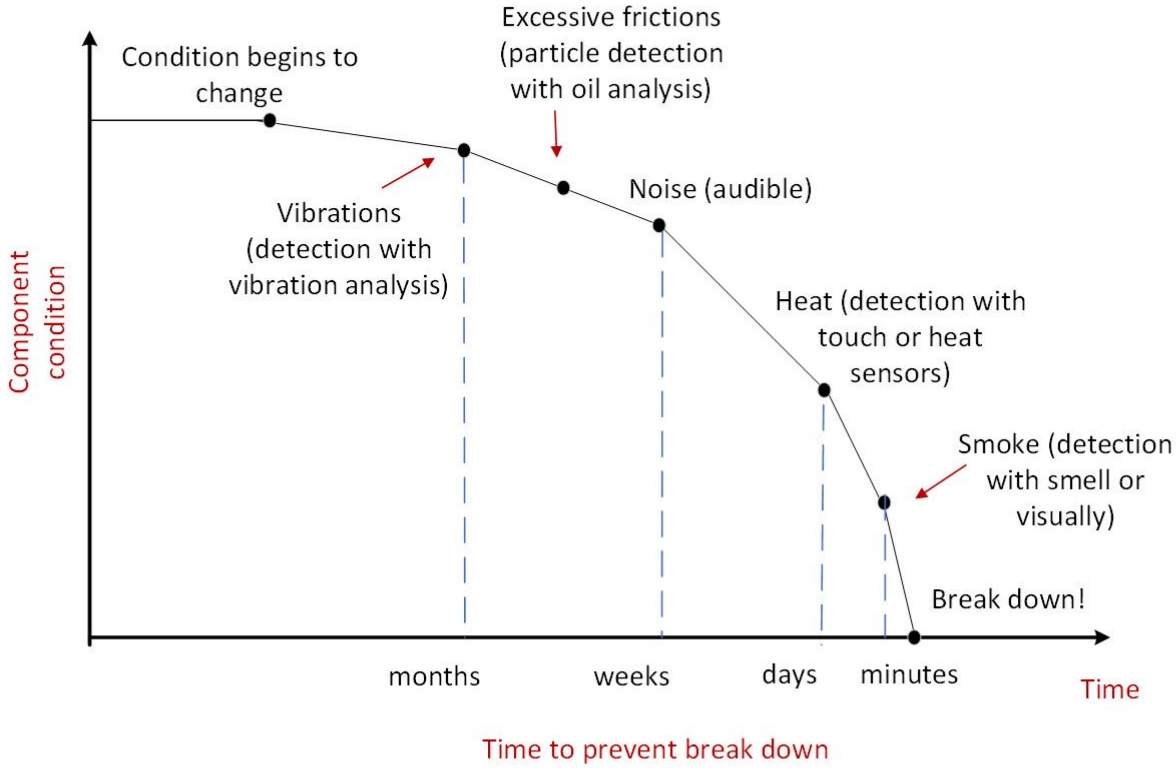


Figure 9-8: Depiction of the progress of a mechanical failure.

WT monitoring systems

Monitoring techniques

Oil analysis

- Oil condition monitoring is performed on gearboxes
- Oil properties are monitored, lubricant quality is assessed and filter system is checked, so that a need for oil change can be performed on time
- Oil condition monitoring can also give information regarding, e.g. the wear debris, so faults in gearbox components can be detected
- Oil is pumped through component, filter catches metal debris from cracks in gearbox components
- Testing debris amount and type gives information about component condition

WT monitoring systems

Monitoring techniques

Oil analysis

- Oil analysis includes: viscosity and oxidation analysis, water or acid content, temperature, machine wear, particle count analysis
- Sensor for particle counting monitors wear debris production, large particles are detected
- Sensors for particle concentration monitor level of oil cleanliness
- Oil monitoring techniques can be online real-time (more expensive) or offline (oil samples)
- For online, several sensors are installed in lubrication loop of gearbox and analysis is performed with electromagnetic, pressure-drop or optical debris sensing

WT monitoring systems

Monitoring techniques

- SHM systems monitor the condition of rotor blades and support structures
- Strain measurement is an important technique for load monitoring in rotor blades and damage detection
- It involves the installation of foil strain gauges or fibre-optical strain gauges in critical parts of the blade
- High number of sensors must be installed for small damages to be detected
- Deflection-based techniques (e.g. laser technology) monitor condition of rotor blades

WT monitoring systems

Monitoring techniques

- When wind and rotor speed, pitch angle etc are considered, deflection can monitor changes in blade bending stiffness. Blade behavior is compared to one in the past or of other blades, to detect changes due to icing or others
- Optical fiber monitoring is another method for SHM of turbine
- It involves the installation of several sensors in the blade, for strain measurement, temperature to detect overheating, acceleration to monitor pitch angle and motor position, measurements for crack and lighting detection

WT monitoring systems

Monitoring techniques

- Sensors for monitoring onshore and offshore support structures: strain gauges, optical fibre sensors, displacement or temperature sensors, accelerometers etc.
- Local methods for SHM (dependence on structure): fatigue monitoring, scour & grouted-joints, splash-zone, corrosion monitoring
- Global methods detect faults that cause changes to modal parameters of structure, e.g. vibration-based approaches

WT monitoring systems

Monitoring techniques

Acoustic emissions

- Acoustic emissions based monitoring can be applied to bearing, gearboxes, blades, shafts
- Developing damages in turbine components, e.g. cracking, debonding, will release energy in the form of transitory elastic waves inside the material
- Acoustic emission analysis can be used to detect faults in high-frequency vibrations, from 50 kHz to 1 MHz
- Parameters measured include amplitude, root mean square value, energy, kurtosis, crest factor
- Can be performed with piezoelectric transducers or optic fiber sensors
- High cost, high number of sensors required

WT monitoring systems

Monitoring techniques

Temperature measurement

- Temperature monitoring of components can detect faults, which can be due to mechanical friction because of damaged bearings or gears, insufficient lubricant properties or faulty electrical connections
- It can be applied to turbine bearings, fluids, generator etc.
- Sensors used are resistant thermometers, optical pyrometers, thermocouples
- Reliable but can’t detect fault at early stage, since temperature develops slowly

WT monitoring systems

Monitoring techniques

Thermography analysis

- Thermography analysis monitors changes in heat emitted by turbine components
- It uses infrared (IR) temperature emitters and high-resolution IR cameras
- Can be applied to gearboxes, bearings, motors, generators etc.
- Like temperature measurement, it can’t detect early faults
- Has high costs due to expensive sensors it requires

WT monitoring systems

Monitoring techniques

Other techniques

- Ultrasonic testing is a potentially effective too, can detect early faults in blade or tower
- Based on elastic wave propagation and reflection within material, can estimate location and nature of failure but requires scanning methods
- Other techniques in development phase or too expensive to be yet commercial include: shaft torque and torsional vibration measurement,
  radiographic inspection,
  electromechanical-parameter based monitoring,
  shock pulse methods

WT monitoring systems

SCADA

- Nearly all wind turbines incorporate a supervisory control and data acquisition (SCADA) system to record operating and environmental conditions
- SCADA collects data from system and sends them to central computer for monitoring and control purposes
- Collects data in 10-minute intervals with sensors in turbine system, like anemometers, thermocouples, switches
- Standard data include wind speed & direction, active & reactive power, ambient temperature, pitch angle, rotational speed

WT monitoring systems

SCADA

- In modern turbines, SCADA can also collect temperature measurements from components like gearbox, lubrication system, generator, nacelle
- Turbine generator shaft speeds and generator currents and voltages also recorded
- Minimum, maximum value, standard deviation also available to operator
- SCADA is sometimes used for CM, cheap solution, can give information regarding turbine performance

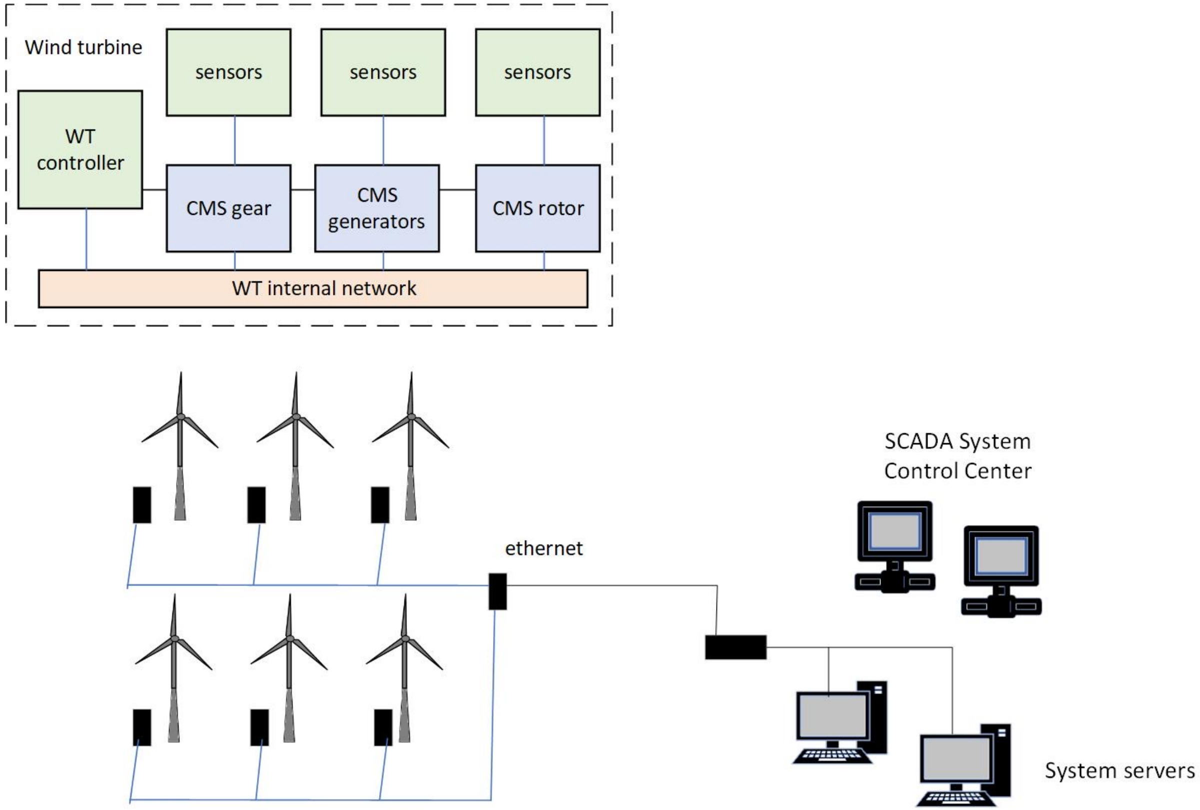


Figure 9-9: Schematic of a SCADA system incorporated in a wind farm.

WT monitoring systems

SCADA

- SCADA data can be used for CM with the use of signal trending, artificial neural networks (ANN) or physical models
- Signal trending compares SCADA data with data from other turbines
- ANN and physical models, model normal turbine operation behavior, using historical data
- SCADA data used as input to predict desired parameters values and identify deviations
- SCADA system can’t replace professional CM systems, doesn’t collect necessary signals for full CM, low sampling frequency, 10-minute interval too slow to detect most rotating machine faults

WT monitoring systems

Future CMS requirements

- CMS become more vital for wind turbine successful operation
- Further improvements needed to address modern issues
- Many turbines are remote or offshore, limited access during the year, rely on CMS
- CMS must increase accuracy in their predictions and fault detection to avoid repairs or components replacements that are costly
- Different turbine technologies present faults in various components, vibration analysis isn’t enough, other CM techniques need to be commercially available

WT monitoring systems

Future CMS requirements

- Larger turbines are subject to more faults, due to higher complexity in design and operation parameters
- New CMS need to take size into account, faults in large turbines cause higher economical costs
- Technological improvements mean that more complicated control systems will be used
- CMS need to improve predictions of electrical, electronic faults
- CMS need to be more cost-effective, large wind farms need high numbers of CMS

Balance of plant

- Balance of plant refers to the number of all other components, except turbine, required for the transfer of power from wind turbine to electric grid
- Foundations are a key component in a wind turbine infrastructure
- Turbines are very tall, foundations are vital in terms of costs and materials
- Foundations are used to transfer vertical load to the ground
- Wind interacts with force with the turbine rotor, at the top of the tower, with a tendency to knock the turbine over

Balance of plant

- Large moment loads are applied to foundations
- Turbine manufacturers usually have preferred type of foundation
- Two types mostly used, gravity and pile reinforced type
- Foundation is basically a mass of concrete and reinforcement, cast in a way to connect with turbine tower

Figure 9-10: Onshore wind turbine foundation at Toddleburn wind farm, UK

Balance of plant

- Made of concrete, reinforcement, can/basket assembly
- Foundations must be strong enough to provide base support for rest of turbine components above
- Quality is vital, cement pouring must be done carefully, to avoid surface or thermal cracking
- Foundations must meet standard requirements

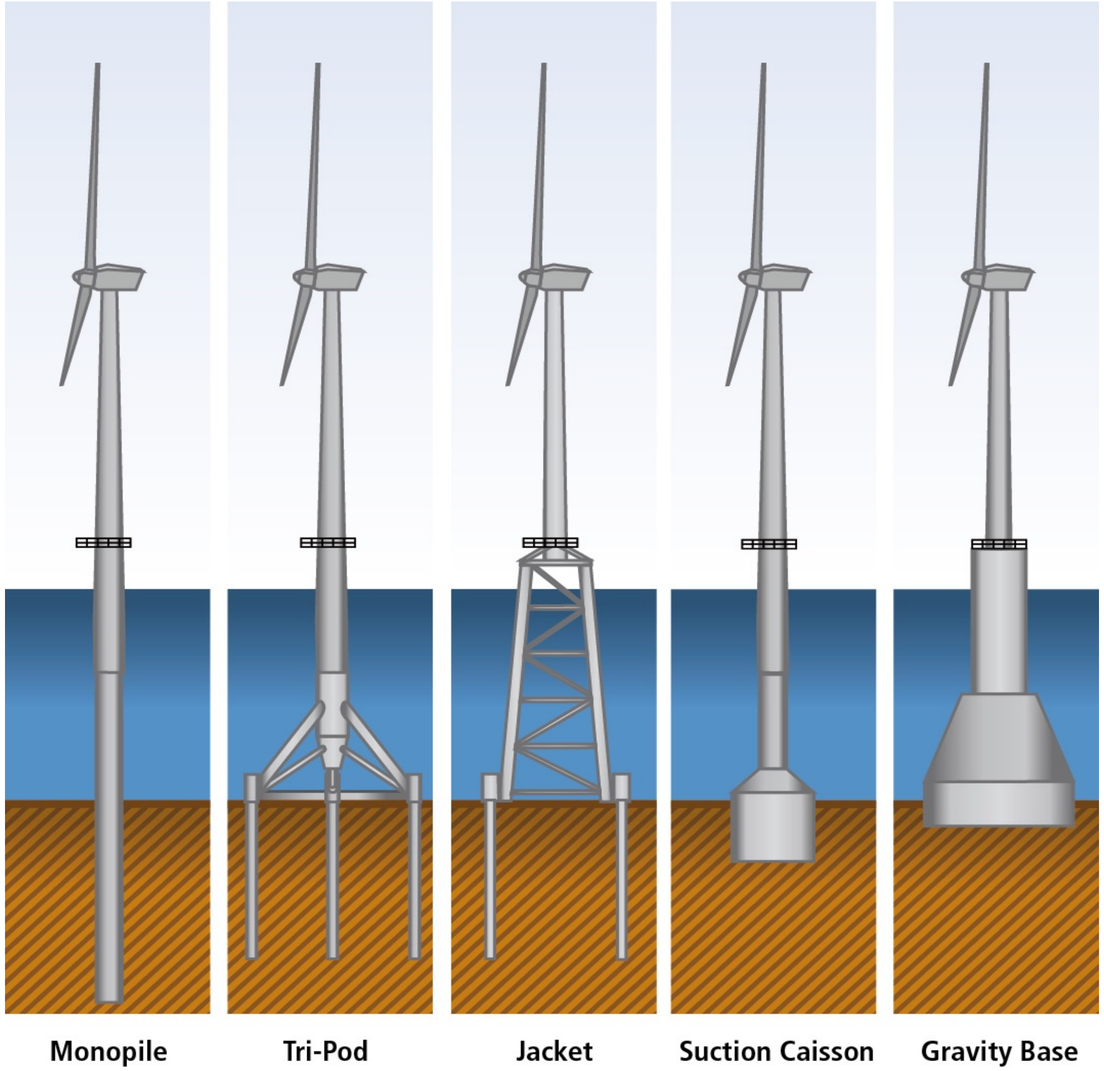


Figure 9-11: Types of offshore wind turbine foundations.

Balance of plant

- Most common type of offshore turbine foundations is the monopile
- Monopile is a single tubular steel pipe
- Large diameter from 4 to 6 meters, installed into the seabed in a depth 5 to 6 times the pile's diameter
- Structural support of turbine is achieved through cohesion of the soil and friction created between pile and soil

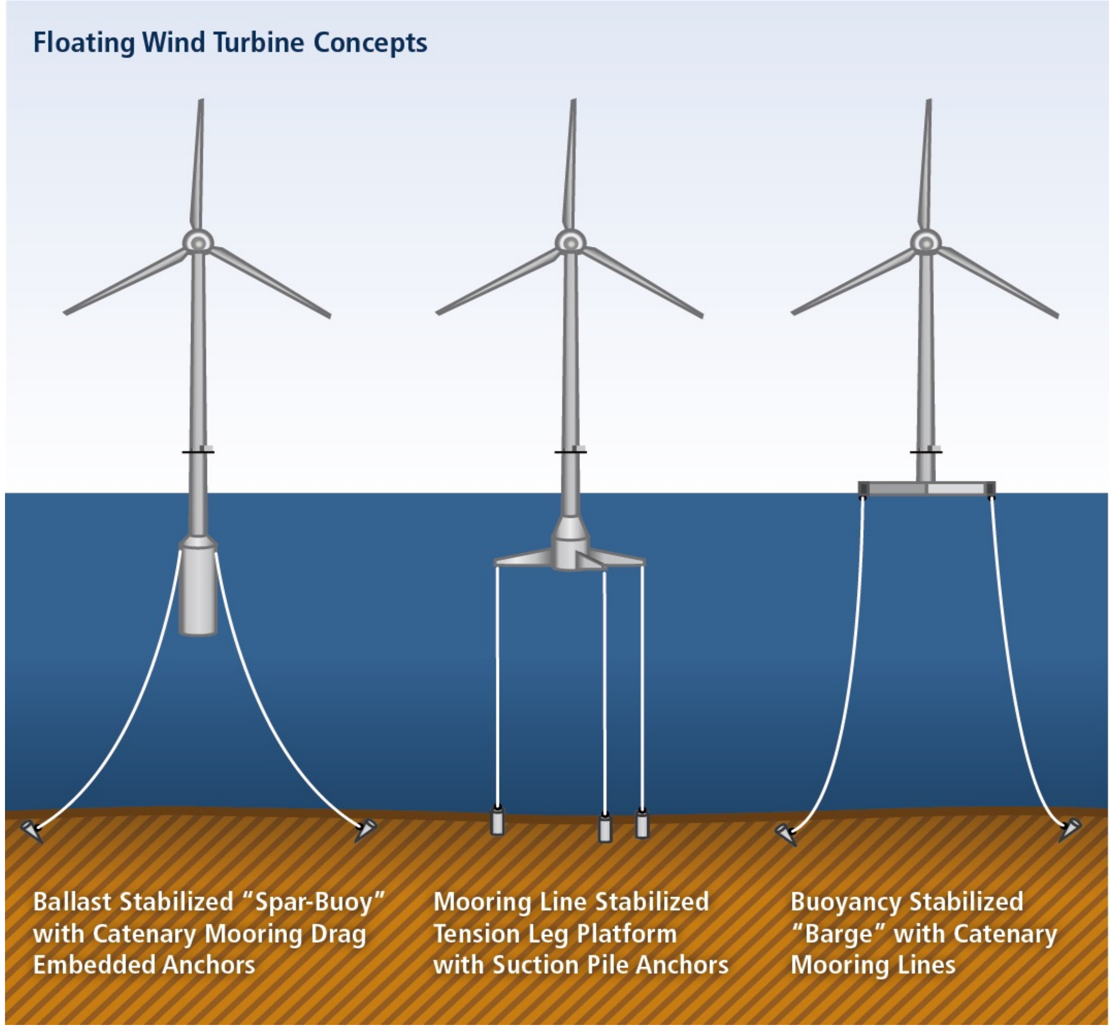


Figure 9-12: Types of offshore wind turbine floating foundations.

Balance of plant

- Roads and infrastructure are another important aspect in wind turbine project
- Turbines are usually in remote areas, vital to have quality roads to provide access to people and machinery for the lifetime of the project
- Roads must be strong enough to carry heavy traffic during project construction and withstand weather conditions
- Roads are usually unpaved, made of compacted layers of crushed rock, gravel and layer of polyethelene geogrid

Balance of plant

- Road network includes site access roads, connecting the site with public roads and wind farm network roads, connecting each turbine with other structures of wind farm
- Construction of roads must follow set requirements
- Infrastructure of wind farm includes a substation, for housing electrical, safety and operational equipment
- Required standards for substation construction, electrical components include power protection systems, switchgear, electric meter
- External transformer area with earthed fencing also usually constructed

Balance of plant

- Cable network is used to transmit generated power from each turbine to substation
- Cables usually installed underground, each cable has length around 0.5 km
- Another set of cables connects substation with closest distribution line, usually installed overhead
- Cables characteristics depend on rated power from wind farm and transmission voltage on the downstream of substation
- Point of connection includes the commissioning of required components to connect to distribution network (switches, reinforcements, supports)

Balance of plant

- SCADA is another wind farm component to monitor and control remote operations in real time
- Cost of SCADA system depends on system complexity and desired available information
- Transformers used in turbines to increase voltage of generated electricity, to limit losses by electricity transmission
- Each transformer has characteristics depending on rated power by turbine, voltage level, transformation ratio
- Other components contributing to overall cost: transportation, site facilities, topographic survey, ground investigation etc.

Standards and technical specifications

- Wind turbine standards refer to design requirements a turbine must have to be operational
- Standards cover most aspects of turbine life, from location conditions to turbine components requirements
- Technical specifications are guidelines and recommendations regarding the turbine design
- Wind turbine standards were first developed by each country
- Nowadays a key body on turbine standards is the International Electrotechnical Commission (IEC), which began international certification in 1995

Standards and technical specifications

- The key standard is IEC 61400, a set of design requirements to ensure longevity and efficient operation of turbine
- International standards can replace those set by national bodies, leading to global certification
- Most important is IEC 61400-1, developed in 2005, focuses exclusively on design requirements
- IEC 61400-1 mostly refers to large onshore turbines but can be applied to small turbines or offshore applications also

Standards and technical specifications

- IEC 61400-2, 2005, deals with safety requirements for small wind turbines
- IEC 61400-3, 2008, refers to design requirements for offshore wind turbines that are not covered by IEC 61400-1 and deals with issues regarding waves, ocean currents etc.
- IEC 61400-4, developed as a revision for International Standard Organization ISO 81400-4, refers to design requirements of turbine gearboxes, for turbines from 40 kW to 2 MW

Standards and technical specifications

- IEC 61400-6, 2020, deals with design requirements for the turbine tower and foundation
- IEC 61400-11 TS is a technical specification from 2006, refers to measurement techniques for acoustic emissions from turbines
- IEC 61400-12, 2005, deals with measurements of power performance for electricity producing turbines
- IEC 61400-13 TS refers to measurements of mechanical loads

Standards and technical specifications

- IEC 61400-14 refers to the apparent sound power levels and tonality of wind turbines
- IEC 61400-21 covers the power quality measurements, which are important for electrical and electronic turbine components
- IEC 61400-22 TS deals with conformity testing and certification of wind turbines
- IEC 61400-23 TS deals with the full-scale structural testing of turbine rotor blades

Standards and technical specifications

- IEC 61400-24 TR is a technical report, refers to protection from lighting
- IEC 61400-25 deals with communications for monitoring and control of the turbines
- IEC 61400-26 TS refers to time-based and production-based availability for wind turbines
- IEC 61400-27 is concerned with the electrical simulation models for wind turbines

Standards and technical specifications

- Other standards, used in USA to complement offshore turbines standards are ISO 19900 with general requirements
- ISO 19902/19903 refer to fixed steel and concrete, respectively, offshore structure
- ISO 19904 refers to floating offshore structures
- API RP 2A-WSD (American Petroleum Institute) refers to recommended practice for planning, designing and constructing fixed offshore steel platforms
- Complementary standards are used in the construction of a wind turbine system

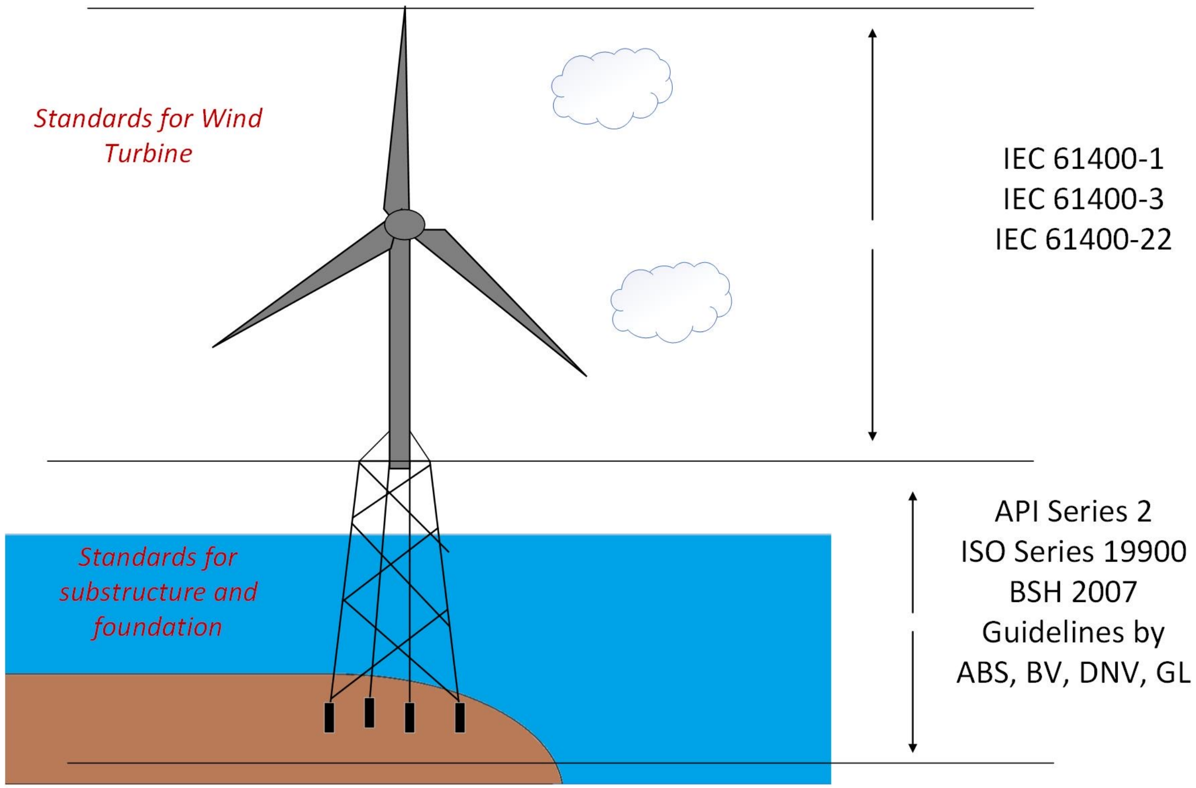


Figure 9-13: Example of the applicability of design standards for offshore wind turbines.

- In this chapter, wind resource and wind forecasting were discussed. Wind turbine monitoring systems were presented. The balance of plant was explained and the wind turbines standards and technical specifications were described.

Summary

Wind Turbines operation and Control (2/2)

Thank You

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Introduction to Renewable Energy

Lecture 10: Energy Storage (1/2)

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Section Outline

Energy Storage is divided into two main Sections.

The aim of Section I is to introduce the student to the main challenges of the electric power industry and show how energy storage is a feasible solution.

The aim of Section II is to introduce the student with the various energy storage systems and their technical characteristics.

Section I

Understanding the Challenges

This week's topics (Section I)

- Historical Overview
- Global Energy Demand
- The Role of Energy in Modern Economies
- The Electric Power Industry
  - Goals of the Electric Power Industry
  - Visual Landscape and Footprint Issues
  - AC versus DC Systems
  - Conventional Power Generation
  - Conventional Power Generation Fuels
  - Emissions and Pollution
  - Emissions Trading System (ETS)
- Glossary
  - Terminology, Units and Conversion Factors
  - Technical Characteristics and Constraints
- Cost of Power Generation
- Examples:
  - Levelized Cost of Energy (LCOE)
    - *Rooftop PV System*
    - *Wind Turbine*
  - Economic Dispatch
  - Optimization
    - *Formulation of an Optimization with Constraints Problem*
    - *Linear Programming including Matlab Code*
- Worldwide Usage of Renewable Energy Sources
- RES Integration Issues and Solutions
  - Issues
  - Solutions
- The Smart Grid

Historical Overview

The Beginning of Electricity

- Historians, Engineers and Scientists disagree on the beginning of Electricity.
  - Greek mathematician Thales of Miletus (624-546BC)
    - *noticed the phenomenon of the fossilized tree resin known as amber which attracted small lightweight objects when rubbed with fur*
  - Benjamin Franklin in 1752 performed the “Kite Experiment”
  - Michael Faraday’s work 1831 - principles of electricity generation
  - etc

Historical Overview

The Beginning of Electricity

- Irrelevant of the major milestones in the area, one thing is for sure.
  - The fact that researchers' fascination with electricity has been around for so many years, proves how little it is known and that there is always room for improvements.

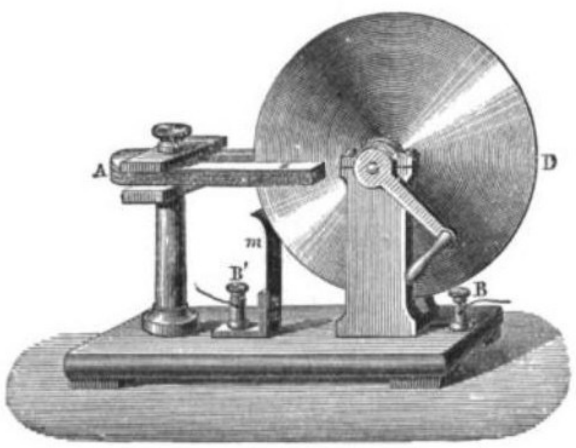


Figure 1: Michael Faraday's Disk Generator (Credit: Émile Alglave Wikimedia Commons Author, Public Domain - Published in USA before 1923 [8])

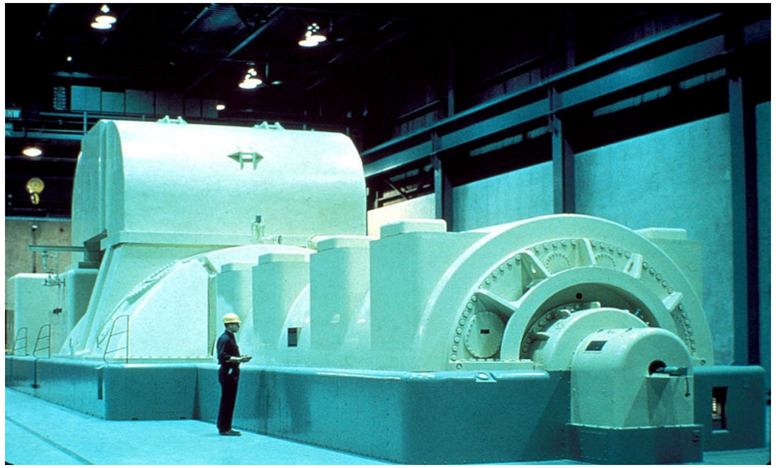
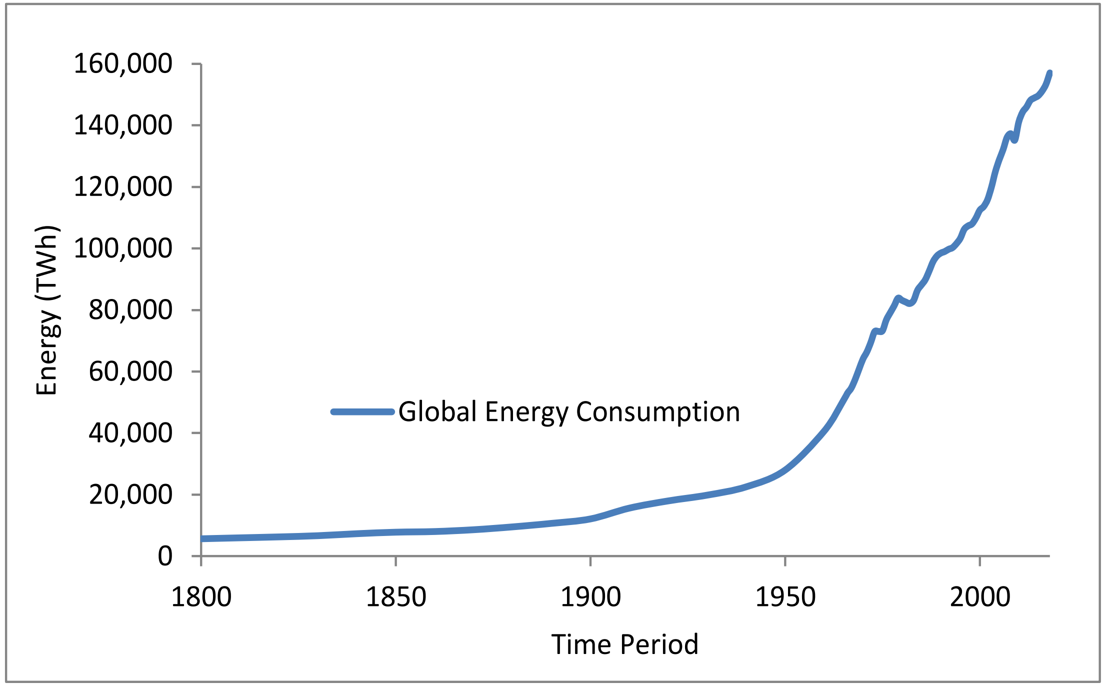


Figure 2: Modern Steam Driven Turbine Generator (Credit: www.nrc.gov [8])

  - Faraday's initial handheld device as shown on Figure 1 looks nothing similar compared to today's generators shown on Figure 2.

Global Energy Demand / Consumption

Historical Trends



- ○ The First Industrial Revolution (1760-1850) included the transition from hand production to steam engine machines and also introduced the electrical telegraph.
- ○ The Second Industrial Revolution introduced new technological systems including electrical power and telephones (19th century) followed by factory electrification (20th century).
  - Therefore, the second industrial revolution also known as the Technological Revolution introduced energy hungry systems and commodities.

The Role of Energy in Modern Economies

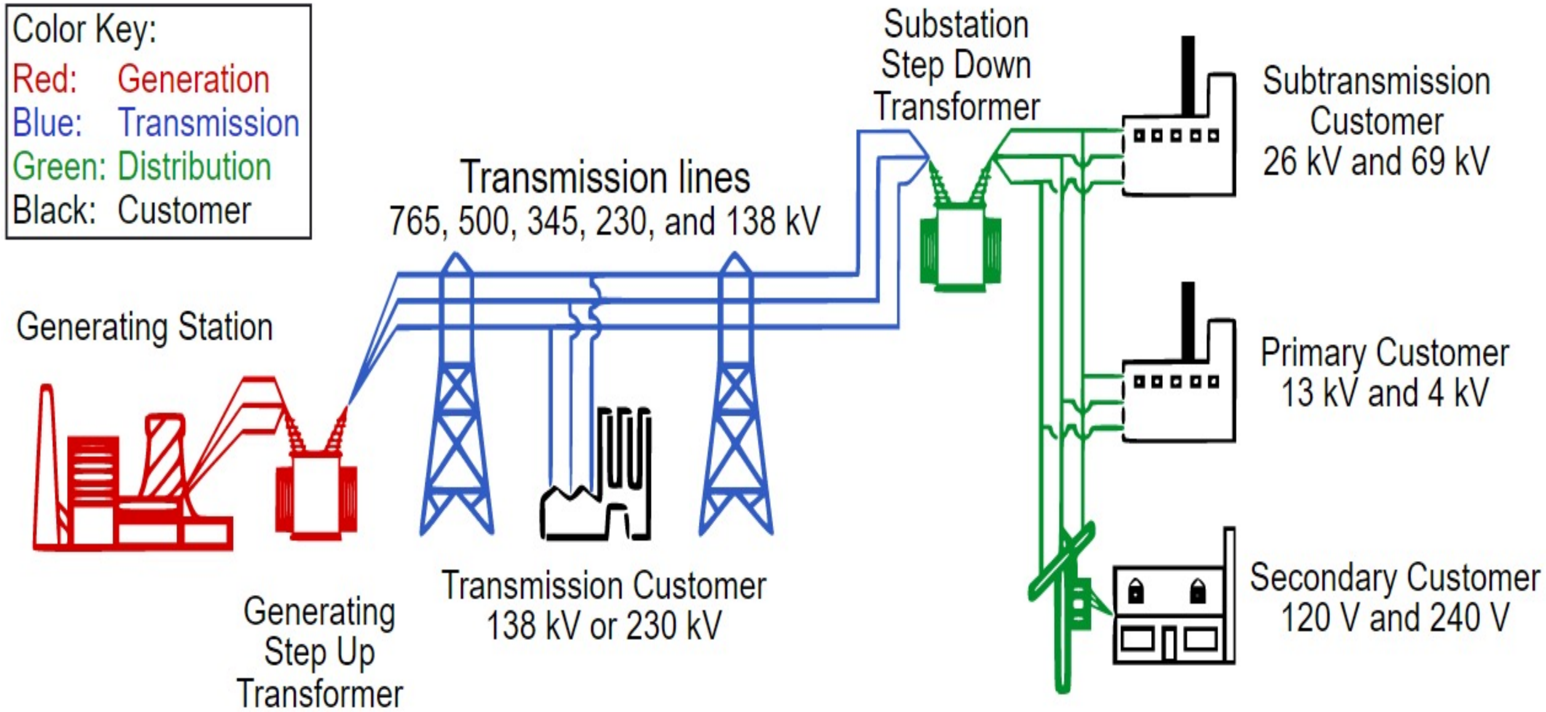
Non-engineering related studies

- Demonstrated
  - The positive relationship between economic growth and energy usage
  - The positive relationship between standard of living and energy usage
  - The negative relationship between standards of living / energy usage / economic development and the family size decreases.
    - *Parents invest more resources in fewer children*

The Electric Power Industry

Three Distinctive Sections

- Generation
- Transmission
- Distribution



Basic Structure of Electric Power System (Credit: United States Department of Energy, Wikimedia Commons author (GNU Free Documentation License - public domain) [19])

Goals of the Electric Power Industry

Three Goals

- The highest reliability standards
- The lowest operation cost
- The minimum environmental impacts

System Reliability

Adequacy and Security

○ "Six Musts"

- Generation capacity must be greater than load
- Transmission must not be overloaded
- Voltages must be within limits
- Must be able to withstand loss of generator
- Must be able to withstand loss of transmission line
- Must not lose stability during short-circuit

Visual Landscape and Footprint Issues

Power Plans and Transmission Lines

- The landscape is affected because of their enormous size.
  - The footprint increases by the need of land clearing, access roads, railroads, and pipelines for fuel delivery, cooling water
  - supplies, etc.

Hunter Power Plant, a coal-fired power plant south of Castle Dale, Utah (Credit: Tricia Simpson, Wikimedia Commons author (GNU Free Documentation License - public domain) [30])

The two coal-fired power plants of the Crystal River North Steam Complex in Crystal River, Florida, (Credit: John Bradley (Ebyabe), Wikimedia Commons author (GNU Free Documentation License - public domain) [31])

Visual Landscape and Footprint Issues

Power Plans and Transmission Lines

- The landscape is affected because of their enormous size.
  - The footprint increases by the need of land clearing, access roads, railroads, and pipelines for fuel delivery, cooling water
  - supplies, etc.

High Voltage Transmission Tower and Lines. Auburn WA, (Credit: Ron Clausen, Wikimedia Commons author (GNU Free Documentation License - public domain) [32])

Close View of a 500kV Lines, Southern California Edison's Path 26 (Credit: Raumfahrt Hauptfokus (Henristosch), Wikimedia Commons author (GNU Free Documentation License - public domain) [33])

AC versus DC Systems

Feud between Edison and Tesla

- Edison was an advocate of Direct Current (DC)
- Tesla of Alternating Current (AC)
- Techno-economic studies show:
  - The AC system is the preferred method because it requires half the initial cost/investment and remains cheaper for transmission lines up to 500-600km.
  - For longer transmission lines then the DC systems are more economical.
  - DC transmission lines are approximately half the size of AC transmission lines.
    - *Therefore, DC transmission lines could offer a lower impact on the environment because of their reduced footprint.*

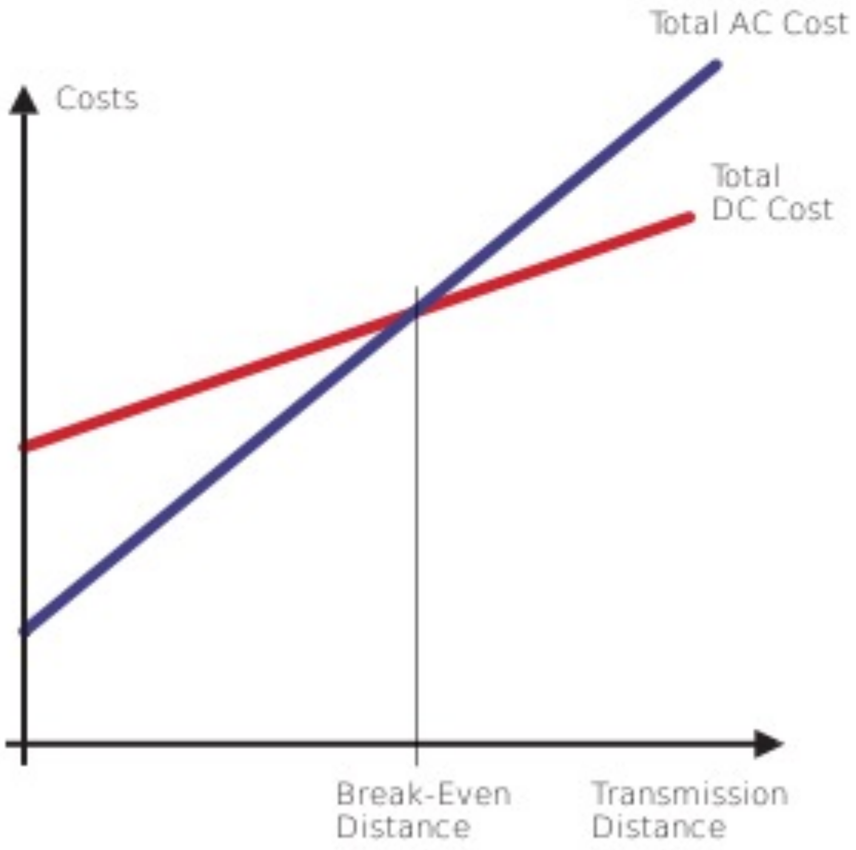
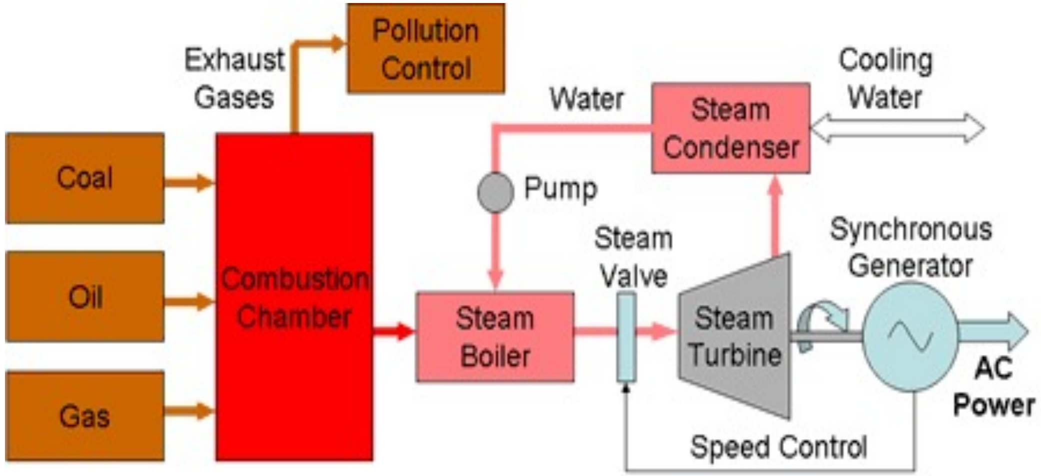


Diagram Costs over line Length (Distance) in Comparison HVAC 3-phase Systems versus HVDC Systems (Credit: Wdwd, Wikimedia Commons author (GNU Free Documentation License - public domain) [34])

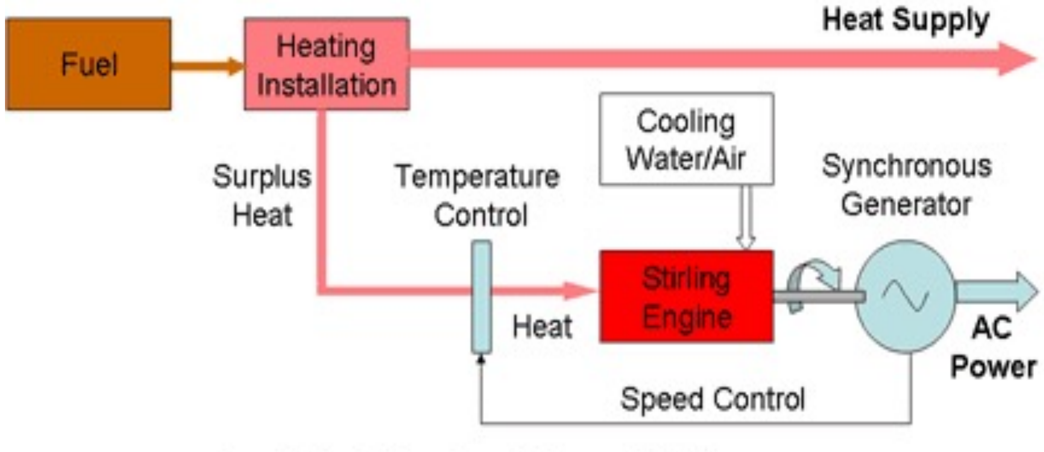
Power Generation

Conventional and Combined Heat and Power (CFP)

- Conventional Power Generation
  - Fuel is burned to heat the water to its boiling point, to create steam which rotates the turbine which produces electricity at the output side.
- Combined Heat and Power (CFP)
  - An internal combustion engine or a stirling engine are used to produce electricity and heat.



Conventional Power Generation Block Diagram [42]

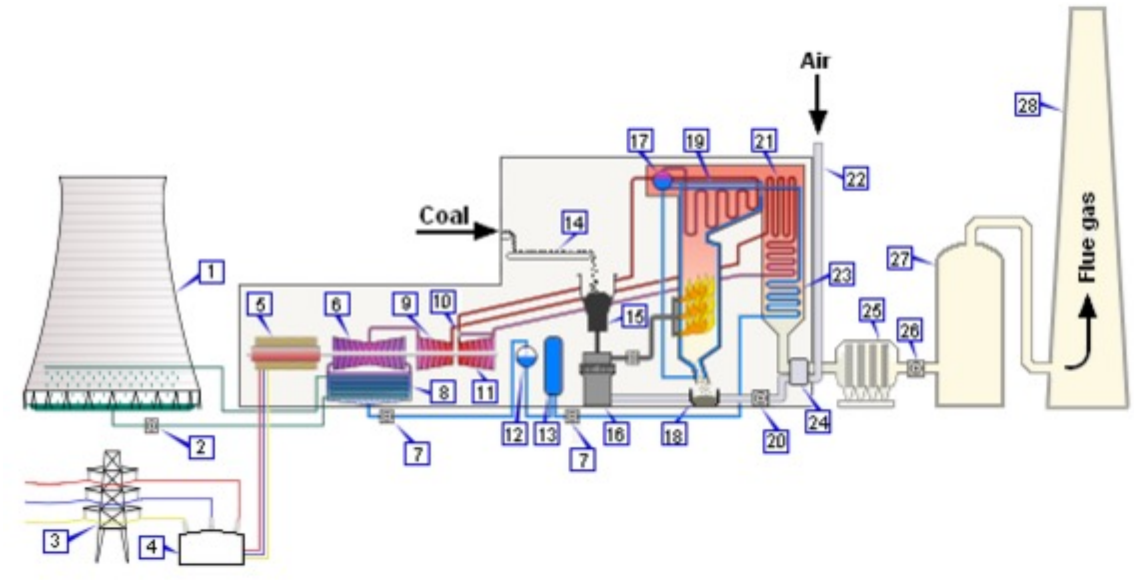


Combined Heat and Power (CHP) Block Diagram [42]

Detailed Conventional Power Station Layout

Various Required Parts

- Power stations are composed of many more parts; safety valves, governors, feeders, pumps, fans, etc.



Detailed Conventional Power Station Layout (Credit: C. Bill (BillC) Wikimedia Commons author (GNU Free Documentation License - public domain) [43])

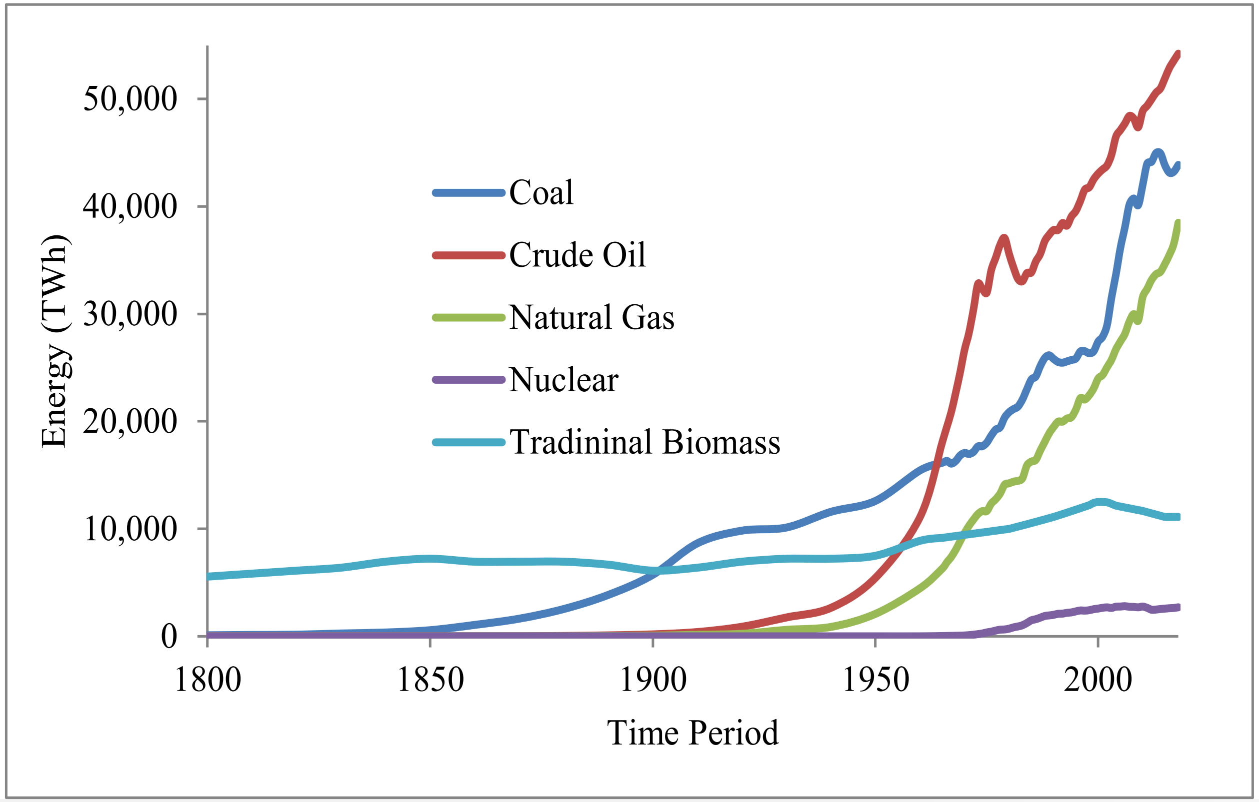
Detailed Conventional Power Station Layout

Index	Description	Index	Description
1	Cooling Tower	15	Coal Hopper
2	Cooling Water Pump	16	Pulverised Fuel Mill
3	Pylon (Termination Tower)	17	Boiler Drum
4	Step-up Transformer	18	Ash Hopper
5	Generator	19	Superheater
6	Low Pressure Turbine	20	Forced Draught Fan
7	Boiler Feed Pump	21	Reheater
8	Condenser	22	Air Intake
9	Intermediate Pressure Turbine	23	Economiser
10	Steam Governor	24	Air Preheater
11	High Pressure Turbine	25	Precipitator
12	Deaerator	26	Induced Draught Fan
13	Feed Heater	27	Chimney Stack
14	Fuel Conveyor		

Conventional Power Generation Fuels

Coal, Crude Oil, Natural Gas, traditional Biomass and Nuclear

- Until 1900s traditional biomass primarily included the use of wood, whereas nowadays biomass includes crops, garbage, landfill gas, alcohol fuels, etc. Furthermore, after 1950 coal has become the primary source of fuel to be replaced by crude oil approximately in the 1970s.



Conventional Power Generation Fuels

Emissions and Pollution

- The by-products when these fuels are burned include carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) and heavy metals such as mercury. The negative impacts to the environment of all these by-products are as follows:
  - CO_2 is a greenhouse gas, which contributes to the greenhouse effect.
  - SO_2 causes acid rain, which is harmful to plants and to animals that live in water.
  - SO also worsens respiratory illnesses and heart diseases, particularly in children and the elderly.
  - NO_x contribute to ground-level ozone, which irritates and damages the lungs.
  - PM results in hazy conditions in cites and scenic areas and coupled with ozone, contributes to asthma and chronic bronchitis, especially in children and the elderly. Very small, or fine PM, is also believed to cause emphysema and lung cancer.
  - Heavy metals such as mercury are hazardous to human and animal health.

The Clean Air Act

Regulation of air emissions from stationary and mobile sources

- Because of the Clean Air Act, power plants control emission by treating the gases before released to the atmosphere. Some of the control devices:
  - Bag-houses: Filters that trap particulates.
  - Electrostatic precipitators: Electrically charged plates that attract and remove particulates.
  - Wet scrubbers: Liquid solution that removes PM.
  - Dry scrubbers: Mix lime in the fuel (i.e. coal) or spray the lime solution into combustion gases to reduce SO_2 emissions.
  - Fluidized bed combustion also results in lower SO_2 emissions.
  - NOx emissions controls include low NO_x burners during the combustion phase or selective catalytic and non-catalytic converters during the post combustion phase.

Emissions Trading System (ETS)

The Carbon Market for Climate Change Mitigation

- Controlling the amount of emissions released in the atmosphere does not imply their complete elimination (reduced to zero).
- Therefore, in 2007 an Emissions Trading System (ETS) was discussed by the International Carbon Action Partnership (ICAP) for climate change mitigation. ETS basically created a carbon market, put a price on carbon and enabled trading between countries to avoid the penalties.
- In the EU as part of the Energy and Climate action reporting showed that ETS works.
  - In 2020 it was reported 21% decrease compared to 2005 whereas the EU 2030 climate and energy framework expects a 43% cut compared to 2005.
- Worth reminding that carbon includes both power generation and automobile emissions.

Glossary

Terminology, Units and Conversion Factors

- The electric power industry is multi-disciplinary and it involves the conversion from one type of energy to another.
  - For example, the conventional power generation process involves the burning of fuels such as oil, gas, coal, etc. Therefore, it is important to quantify the amount of energy released during combustion.
- The quantification of the heating value is also known as energy or calorific value.
- The units for the volumetric and gravimetric calorific values are given by Joules/Litter (J/L) and Jules/kg (J/kg) respectively.

Glossary

Essential Units and Conversion Factors

1 barrel of oil = 158.987294928 L
1 kWh = 3.6 MJ
1 Btu = 1055.056 J
1 therm = 105.5056 MJ
1 calorie = 4.1868 J
1 tonne of oil equivalent (toe) = 41.868 GJ (LHV)
1 barrel of oil (LHV) ≈ 5.70 GJ (IEA def.)
1 barrel of oil (LHV) ≈ 5.86 GJ (global avg.)
1 mechanical hp ≈ 745.7 W
1 PS ≈ 735.5 W
10,000 TWh/y ≈ 1.14 TW (peak power)

Glossary

Technical Characteristics and Constraints

- **Capacity or maximum power** - The maximum (Pmax) output of a plant, in (MW)
- **Minimum Operating Limit** - The minimum (Pmin) amount of power a plant can generate once it is turned on, in (MW)
- **Start-up and Shut-down Costs** - These are the costs involved in turning the plant on and off, in ($/MWh). Start-up and Shut-down Costs could be different according to the technology used.
- **No-Load Cost** - The cost of turning the plant on, but keeping it in an idle state ready to increase power output, in ($/MWh).
- **Minimum Run Time** - The shortest amount of time a plant can operate once it is turned on, in (h).
- **Start-up or Ramp time** - The amount of time it takes from the moment a generator is turned on to the moment it can start providing energy to the grid at its lower operating limit, in (h).
- **Shut-down time** – The time it takes a generator to stop spinning, in hours (h). If a generator does not stop spinning completely then it cannot be turned back on.
- **Ramp rate** - This variable influences how quickly the plant can increase or decrease power output. This is measured in MW/h or in % of capacity per unit time.

Cost of Power Generation

Levelized Cost of Energy (LCOE)

- The fixed costs include capital (buildings) and land.
  - Capital costs are also known as overnight cost.
- Variable costs are proportional to the amount of generated power and include cost of fuel, maintenance, replacement parts, personnel costs, etc.
- In addition, like any other investment all the costs are analysed using financial methodologies which include the net present value, the time value of money and the discounted cash flow (DCF).
- Breakeven point over the lifetime of the plant is calculated using the **Levelized Cost of Energy (LCOE)** method

Levelized Cost of Energy (LCOE)

Definition

- The breakeven point is regarded as the minimum constant price at which electricity must be sold ($/Wh). The lifetime of the plant is usually considered between 25-35 years. The LCOE method gives a good metric for the plant's performance and it is a good consistent basis for comparison between the various technologies.

$$LCOE = \frac{\text{Total cost of ownership (\$)}}{\text{System production over its lifetime (kWh)}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where,

I_t is the investment costs in the year t

M_t represents the operations and maintenance costs in the year t

F_t is the fuel cost in the year t

E_t is the electrical generated energy in the year t

r is the discount rate

n is the expected lifetime of system or power station

Levelized Cost of Energy (LCOE)

Example 1:

- Assume a rooftop solar PV system will be installed on a commercial facility, and the characteristics of the project are the following:

- Project capacity = 100 kilowatts
- Initial investment = $300,000
- Maintenance costs = $3,000/year (1% of initial investment)
- Estimated yearly production = 182,500 kWh
- Project life = 25 years

- Calculate the levelized cost of electricity.

Levelized Cost of Energy (LCOE)

Example 1: Solution

- Over its lifetime, the total kWh production of this PV system will be:

  Lifetime output = 182,500 kWh/year x 25 years = 4,562,500 kWh

- The total cost of ownership, considering the initial investment and maintenance costs will be:

  Total Cost of Ownership = \$300,000 + \$3,000/year x 25 years = \$375,000

- Therefore, this project will have the following LCOE:

  LCOE = \$375,000 / 4,562,500 kWh = **\$0.0822 / kWh**

Note: If electric utility rates at the project's location are higher than this, the net effect will ; be a reduction in energy expenses.

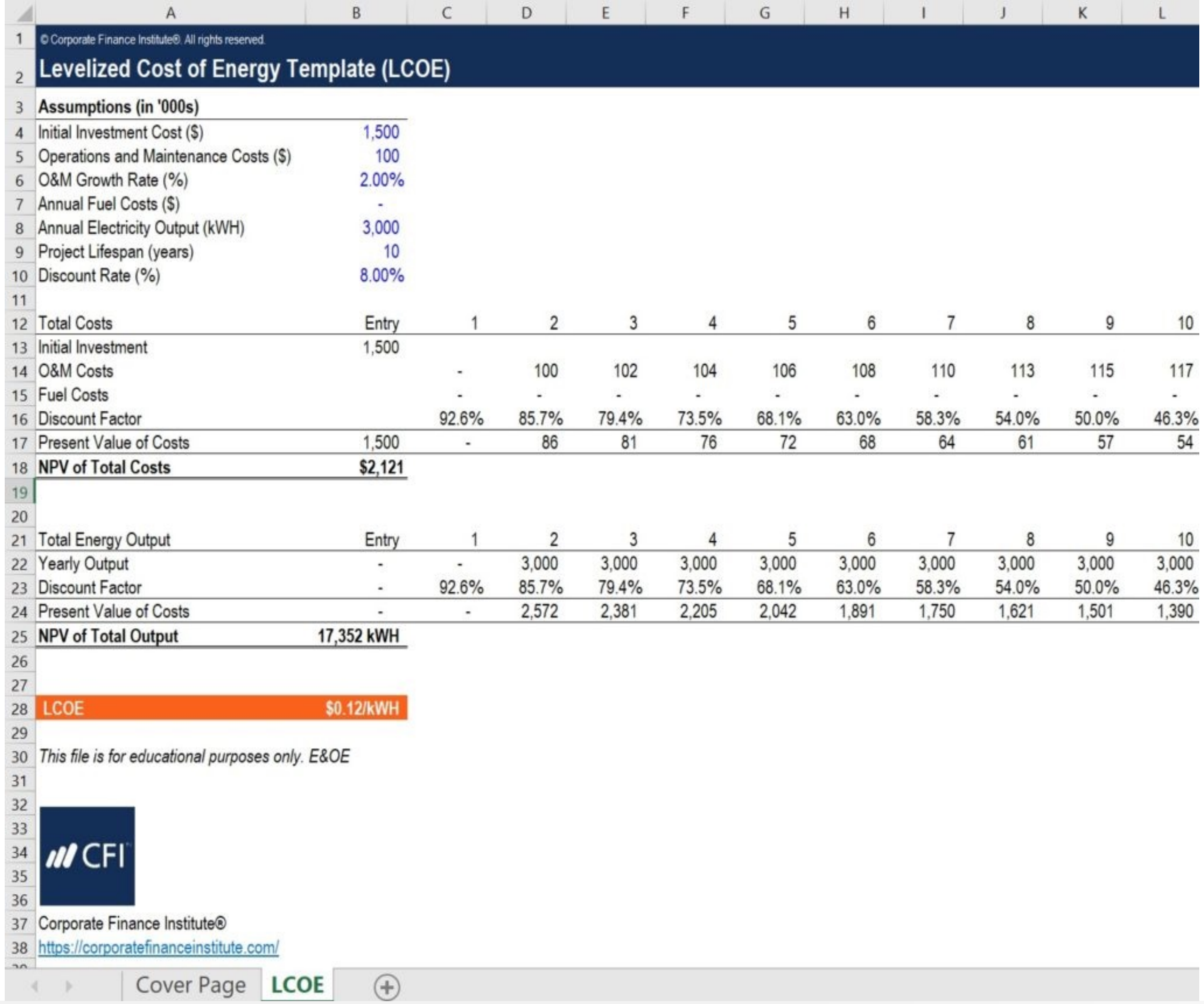
Levelized Cost of Energy (LCOE)

Example 2:

- A hypothetical wind turbine takes one year to build and costs $1.5 million. The operating and maintenance costs are $300,000 per year, with an associated growth rate of 2% annually. There are no associated fuel costs. The wind turbine's lifespan is 10 years, and it is estimated to produce 3 million kWh each year. Finally, the associated discount rate for the project is 8%.

Levelized Cost of Energy (LCOE)

Example 2: Solution using spreadsheet



	A	B	C	D	E	F	G	H	I	J	K	L
1	© Corporate Finance Institute®. All rights reserved.											
2	Levelized Cost of Energy Template (LCOE)											
3	**Assumptions (in '000s)**											
4	Initial Investment Cost ($)	1,500										
5	Operations and Maintenance Costs ($)	100										
6	O&M Growth Rate (%)	2.00%										
7	Annual Fuel Costs ($)	-										
8	Annual Electricity Output (kWH)	3,000										
9	Project Lifespan (years)	10										
10	Discount Rate (%)	8.00%										
11												
12	Total Costs	Entry	1	2	3	4	5	6	7	8	9	10
13	Initial Investment	1,500										
14	O&M Costs		-	100	102	104	106	108	110	113	115	117
15	Fuel Costs		-	-	-	-	-	-	-	-	-	-
16	Discount Factor		92.6%	85.7%	79.4%	73.5%	68.1%	63.0%	58.3%	54.0%	50.0%	46.3%
17	Present Value of Costs	1,500	-	86	81	76	72	68	64	61	57	54
18	**NPV of Total Costs**	**$2,121**										
19												
20												
21	Total Energy Output	Entry	1	2	3	4	5	6	7	8	9	10
22	Yearly Output	-	-	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
23	Discount Factor	-	92.6%	85.7%	79.4%	73.5%	68.1%	63.0%	58.3%	54.0%	50.0%	46.3%
24	Present Value of Costs	-	-	2,572	2,381	2,205	2,042	1,891	1,750	1,621	1,501	1,390
25	**NPV of Total Output**	**17,352 kWH**										
26												
27												
28	LCOE	$0.12/kWH										
29												
30	*This file is for educational purposes only. E&OE*											
31												
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37	Corporate Finance Institute®											
38	https://corporatefinanceinstitute.com/											

Cost of Power Generation

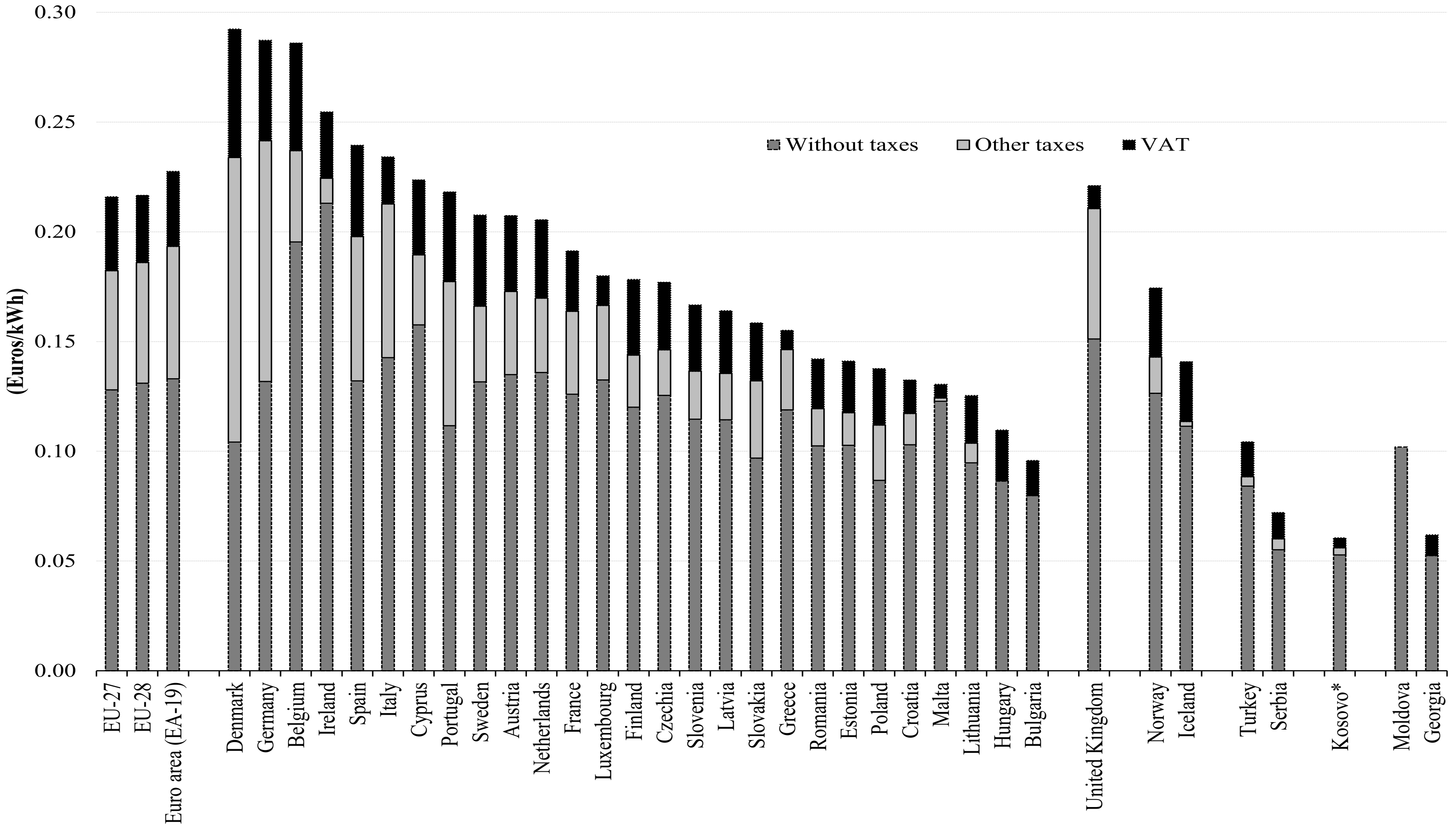
Indicative Capital and Operating Costs

Technology		Capital Cost ($/kW)	Operating Cost ($/kW)
Conventional Sources	Natural Gas Combustion Turbine	400 – 1,000	0.04-0.10
	Natural gas combined-cycle	600 - 1,200	0.04-0.10
	Coal-fired Combustion Turbine	500 - 1,000	0.02-0.04
	Coal Gasification Combined-Cycle (IGCC)	1,000 - 1,500	0.04-0.08
	Coal (with SO_2 and NO_x controls)	3,500 - 3,800	0.04-0.08
	Nuclear	1,200 - 6,000	0.02-0.05
Renewable Sources	Wind (on-shore)	1,600	<0.01
	Wind (off-shore)	6,500	<0.01
	Solar PV (fixed)	1,060 - 1,800	<0.01
	Solar PV (Tracking)	1,130 - 2,000	<0.01
	Geothermal	2,800	<0.01
	Hydro-electric	1,200 - 5,000	<0.01
	Fuel Cells	7,200	N/A
Storage	Batteries	2,000	N/A

Cost of Power Generation

Electricity Prices for Household Consumers

- Customer price for energy consumption includes taxes such as Value Added Tax (VAT) which differ from country to country.
- For example, the country of Denmark has the lowest price of approximately 0.11€/kWh. However, after adding all the additional taxes then Denmark has the highest price among all EU countries of 0.29€/kWh.



Cost of Power Generation

Example 3: Economic Dispatch

Given the following generation unit characteristics and costs, determine what combination of online units should be used to supply 550 MW?

Unit 1: Is a coal-fired steam unit. The minimum output power is 150 MW whereas the maximum output power is 600 MW. The unit's fuel cost is 1.1$/MBtu whereas the Input-Output curve is described by equation 1.

$$H_1\left(\frac{MBtu}{h}\right) = 510 + 7.2P_1 + 0.00142(P_1)^2 \qquad \text{[Equation 1]}$$

Unit 2: Is an oil-fired steam unit. The minimum output power is 100 MW whereas the maximum output power is 400 MW. The unit's fuel cost is 1.0$/MBtu whereas the Input-Output curve is described by equation 2.

$$H_2\left(\frac{MBtu}{h}\right) = 310 + 7.85P_2 + 0.00194(P_2)^2 \qquad \text{[Equation 2]}$$

Unit 3: Is an oil-fired steam unit. The minimum output power is 50 MW whereas the maximum output power is 200 MW. The unit's fuel cost is 1.2$/MBtu whereas the Input-Output curve is described by equation 3.

$$H_3\left(\frac{MBtu}{h}\right) = 78 + 7.97P_3 + 0.00482(P_3)^2 \qquad \text{[Equation 3]}$$

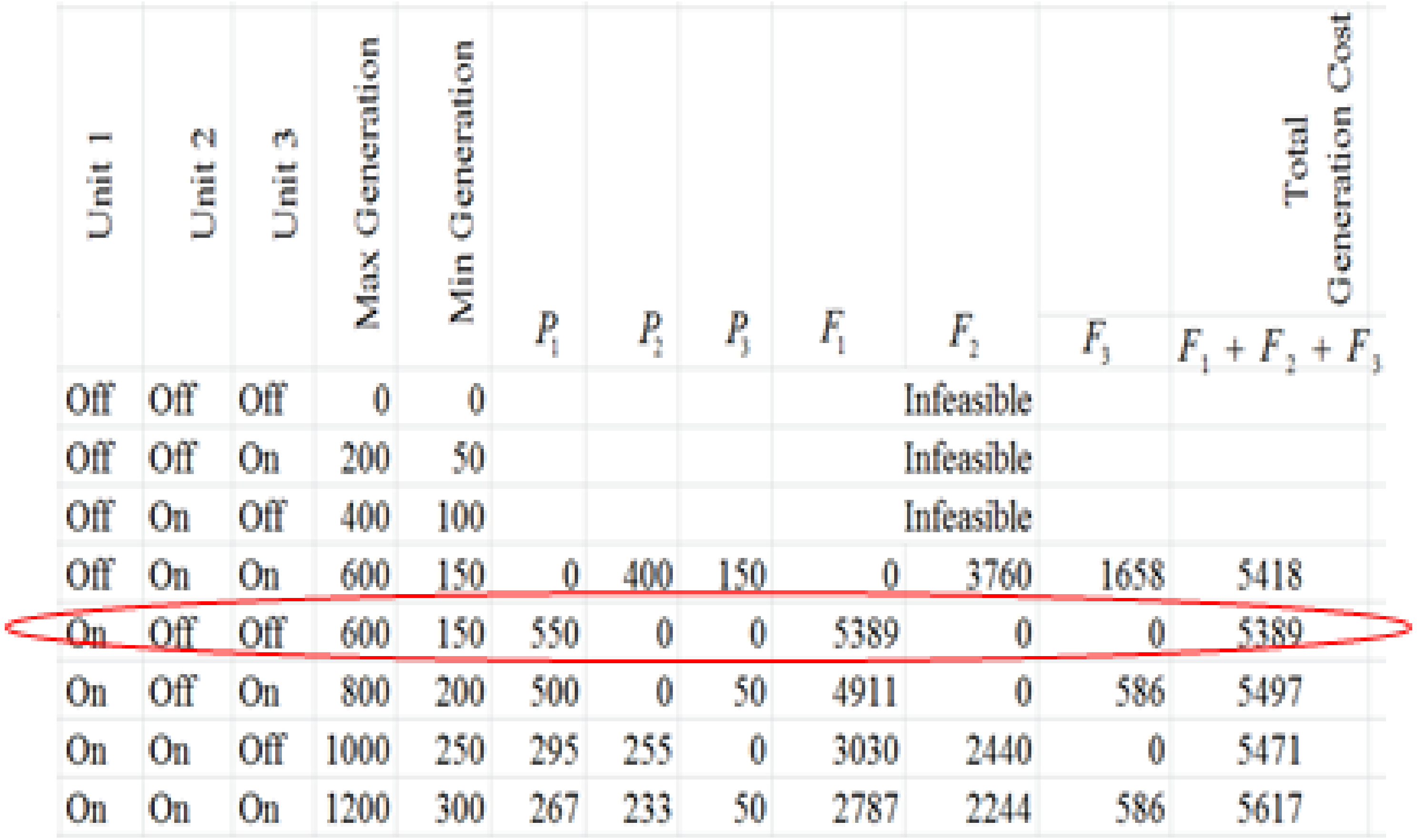
Cost of Power Generation

Example 3: Economic Dispatch Solution

- 1. Test all combinations of the three units
- 2. Do not violate the power limitations (constraints) of each generator; Pmin and Pmax
- 3. Identify feasible and infeasible combinations
  - Infeasible
    - *i. The sum of all maximum MW for the units committed is less than the load or*
    - *ii. The sum of all minimum MW for the units committed is greater than the load*
- 4. For each feasible combination
  - The units will be dispatched using the Economic Dispatch techniques

Cost of Power Generation

Example 3: Economic Dispatch Solution



Unit 1	Unit 2	Unit 3	Max Generation	Min Generation	P_1	P_2	P_3	F_1	F_2	F_3	Total Generation Cost $F_1 + F_2 + F_3$
Off	Off	Off	0	0					Infeasible		
Off	Off	On	200	50					Infeasible		
Off	On	Off	400	100					Infeasible		
Off	On	On	600	150	0	400	150	0	3760	1658	5418
On	Off	Off	600	150	550	0	0	5389	0	0	5389
On	Off	On	800	200	500	0	50	4911	0	586	5497
On	On	Off	1000	250	295	255	0	3030	2440	0	5471
On	On	On	1200	300	267	233	50	2787	2244	586	5617

The complete solution is shown on Figure 18. As shown, for a load of 550 MW then the optimum solution would be when only unit 1 is ON.

Cost of Power Generation

Example 4: Formulation of an Optimization Problem

- Given the following word problem then formulate the profit and constraint equations.
- A factory produces 3 products (A, B and C). Product A requires 2 hours of fabrication, 1 hour of assembly and gives the company a profit of 7. Product B requires 3 hours of fabrication, 1 hour of assembly and gives the company a profit of 8. Product C requires 2 hours of fabrication, 2 hours of assembly and gives the company a profit of 10. The company has 1000 labour hours for fabrication and 800 for assembly.

Cost of Power Generation

Example 4: Solution

- Following the aforementioned methodologies:

1. Assign variables: A → x_1, B → x_2 and C → x_3 (note that variables x_1, x_2.. x_n are preferred in the power electric industry)
2. Objective Function is the Profit, $P = 7x_1 + 8x_2 + 10x_3$
3. Inequality $x_1, x_2, x_3 \geq 0$
    1. (variables such as goods/products, power generation, fuel consumption are either zero or positive)
4. Constraints
    a. Fabrication: $2x_1 + 3x_2 + 2x_3 \leq 1000$
    b. Assembly: $x_1 + x_2 + 2x_3 \leq 800$

Cost of Power Generation

Example 5: Continued

- Given the following word problem then formulate the profit and constraint equations.
- A factory produces 3 products (A, B and C). Product A requires 2 hours of fabrication, 1 hour of assembly and gives the company a profit of 7. Product B requires 3 hours of fabrication, 1 hour of assembly and gives the company a profit of 8. Product C requires 2 hours of fabrication, 2 hours of assembly and gives the company a profit of 10. The company has 1000 labour hours for fabrication and 800 for assembly.
- ***How many products of each type, does the company have to sell to maximise profits?***

Cost of Power Generation

Example 5: Solution Using Linear Programming

- Using the simplex method (Linear Programming) the first step requires that inequality equations are converted to equality with the use of slack variables.

- For example, inequality equations for fabrication (1) and assembly (2) using slack variables S1 and S2 can be rewritten as (3) and (4) respectively:

$$2x_1 + 3x_2 + 2x_3 \leq 1000 \qquad (1)$$

$$x_1 + x_2 + 2x_3 \leq 800 \qquad (2)$$

$$2x_1 + 3x_2 + 2x_3 + S_1 = 1000 \qquad (3)$$

$$x_1 + x_2 + 2x_3 + S_2 = 800 \qquad (4)$$

Cost of Power Generation

Example 5: Solution Using Linear Programming

- Using the simplex system method, the system of equations can be rewritten as:

$$
\begin{array}{c|cccccc|c}
 & x_1 & x_2 & x_3 & S_1 & S_2 & P & \\
\hline
S_1 & 2 & 3 & 2 & 1 & 0 & 0 & 1000 \\
S_2 & 1 & 1 & 2 & 0 & 1 & 0 & 800 \\
\hline
P & -7 & -8 & -10 & 0 & 0 & 1 & 0
\end{array}
$$

- Finally, the maximum possible profit could be \$4,400 when the company sells 200 and 300 pieces of product A (x_1) and product C (x_3) respectively. Product B (x_2) should not be produced.

$$
\begin{array}{c|cccccc|c}
 & x_1 & x_2 & x_3 & S_1 & S_2 & P & \\
\hline
x_1 & 1 & 2 & 0 & 1 & -1 & 0 & 200 \\
x_3 & 0 & -1/2 & 1 & -1/2 & 1 & 0 & 300 \\
\hline
P & 0 & 1 & 0 & 2 & 3 & 1 & 4400
\end{array}
$$

Linear Programming

Example 6: Using Matlab

Using Matlab implement Linear Programming to maximise the objective function subject to constraints and calculate the values for x_1, x_2, and x_3.

Objective function: $f(x_1, x_2, x_3) = 4x_1 + 2x_2 + x_3$

Subject to Constraints:

$$x_1 + x_2 + 2x_3 \leq 6$$

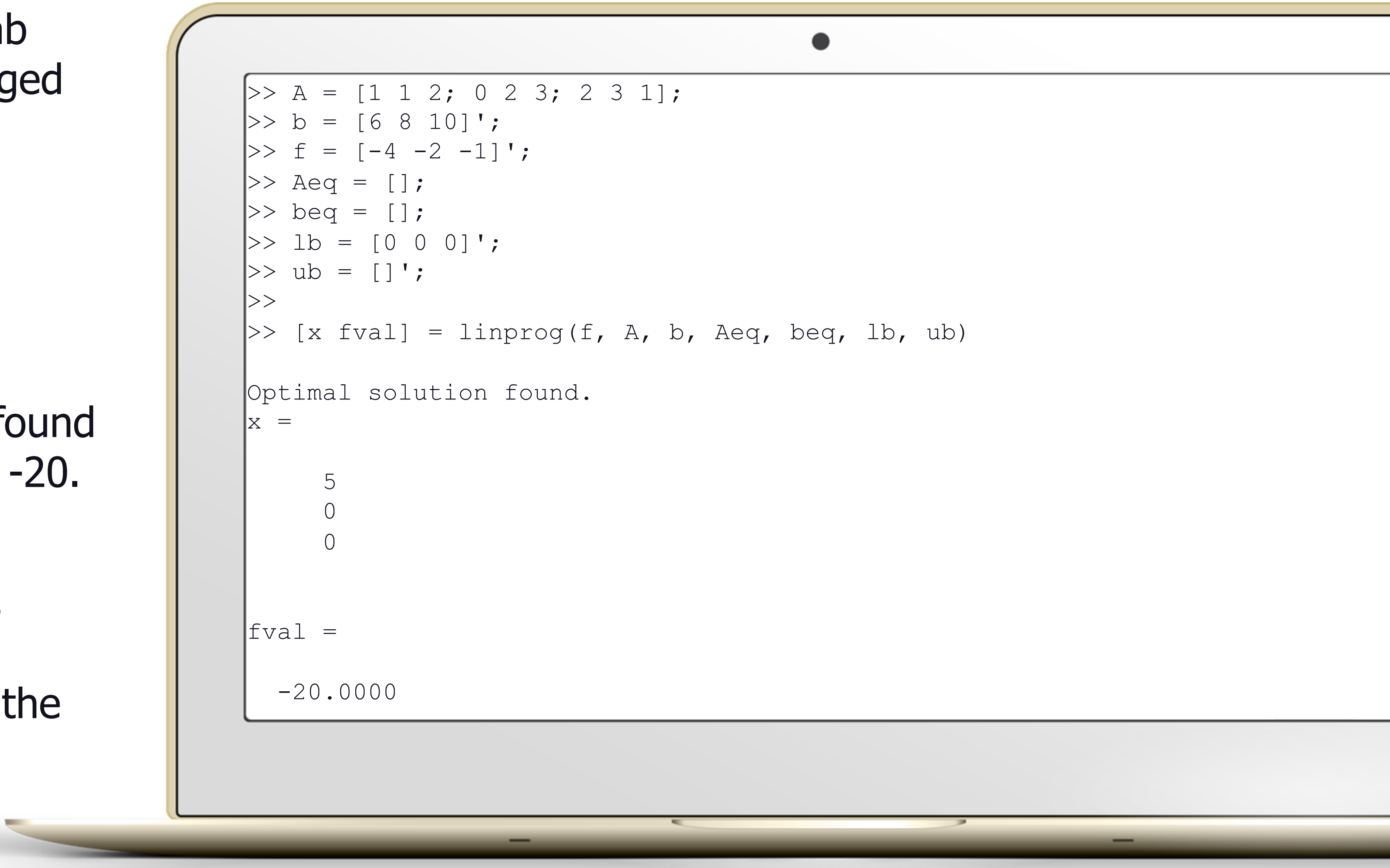
$$2x_2 + 3x_3 \leq 8$$

$$2x_1 + 3x_2 + x_3 \leq 10$$

$$x_1, x_2, x_3 \geq 0$$

Example 6: Solution – Matlab Code

- Therefore, using the Matlab code, it can be acknowledged that the answers are:
- $(x_1, x_2, x_3) = (5,0,0)$
- $(f_{val}) = -20$.
- The value of *f* using the theoretical approach was found to be 20 and Matlab to be -20.
- This is because Matlab is minimizing the function as opposed to required maximization, hence wise the difference in sign.

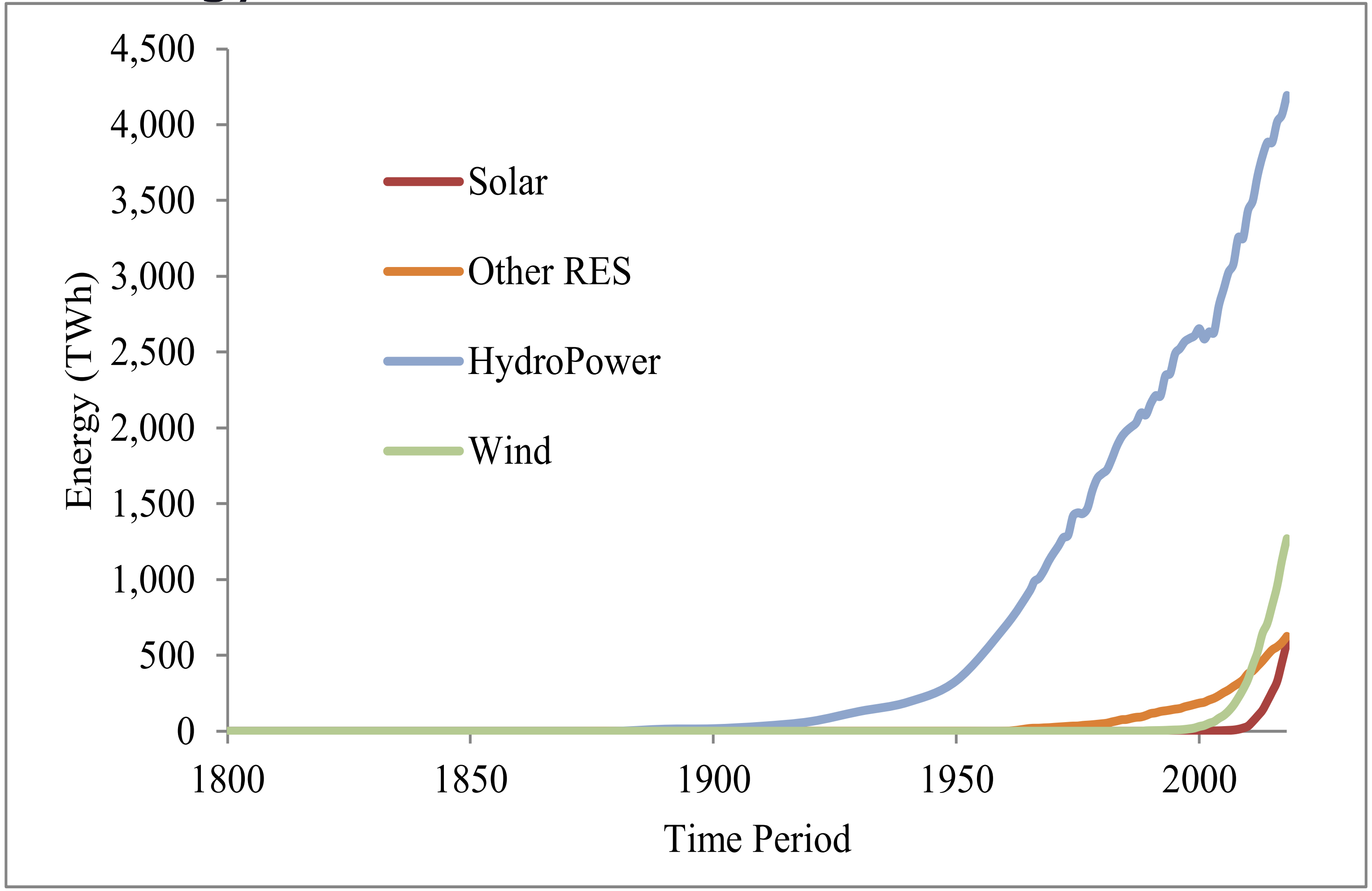


```
>> A = [1 1 2; 0 2 3; 2 3 1];
>> b = [6 8 10]';
>> f = [-4 -2 -1]';
>> Aeq = [];
>> beq = [];
>> lb = [0 0 0]';
>> ub = []';
>>
>> [x fval] = linprog(f, A, b, Aeq, beq, lb, ub)

Optimal solution found.
x =

     5
     0
     0


fval =

  -20.0000
```

Renewable Energy Sources

Worldwide Usage of Renewable Energy Sources

- Alternative methods of power generation which are friendly to the environment; Green Energy or Renewable Sources of Energy (RES) which have zero emissions.
- Renewable Energy Sources include Solar (Photovoltaics (PV), Solar Thermal, Concentrated Solar Thermal (CSP) and Solar Heating), Wind, Hydro, Biomass (organic material that comes from plants and animals), Geothermal, Waves, Ocean Currents and Tidal.



Renewable Energy Sources

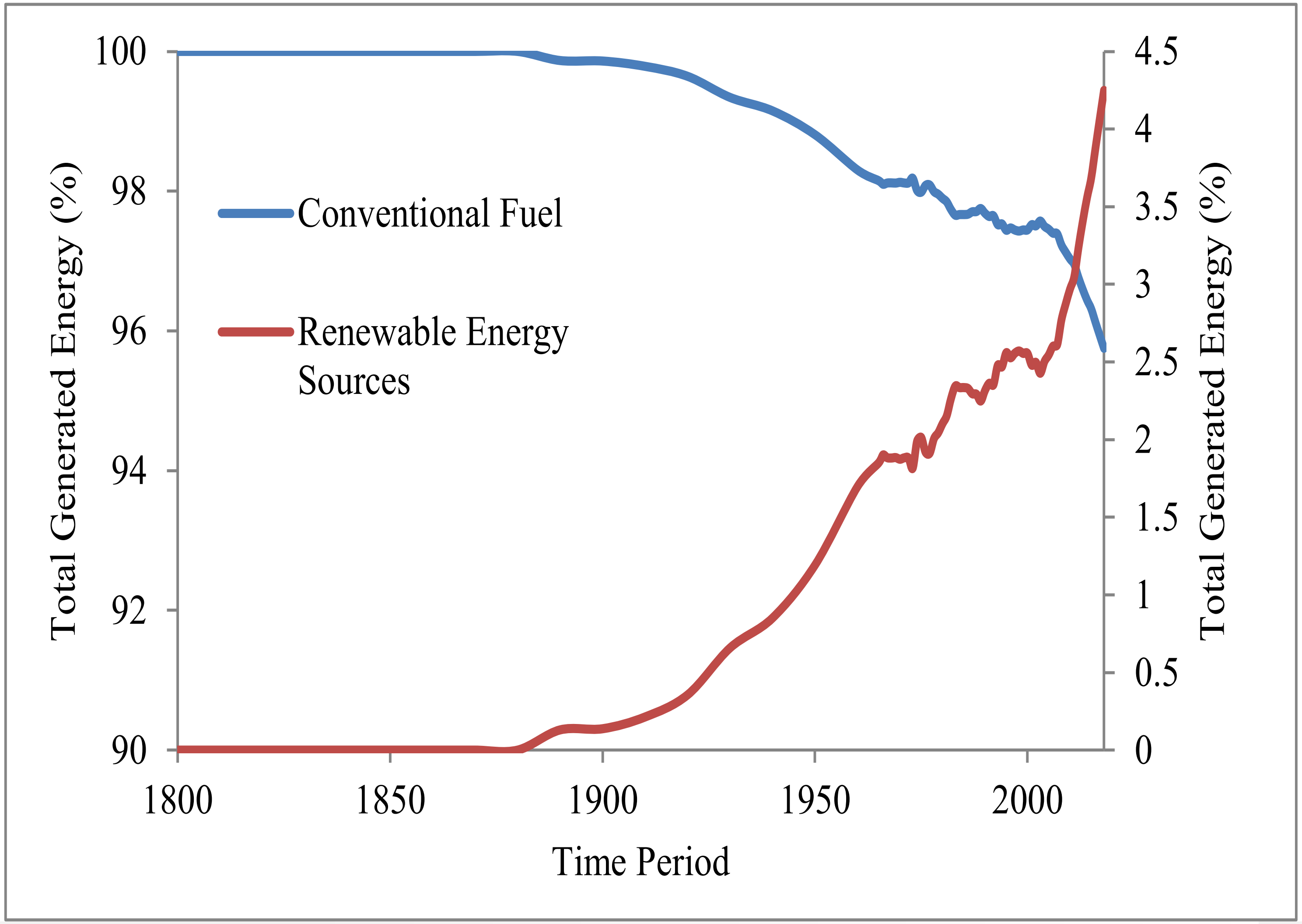
Hydro Power Controversy

- It is controversial whether hydro power should be included in the RES family because mega-dams affect the environment and ecosystem; divert and reduce natural river flows, thus restricting access for animal and human populations.
- On the other hand, small hydroelectric plants divert only a fraction of the river flow hence they are considered as less harmful to the environment.

Renewable Energy Sources

Percentage of Worldwide Generated Power

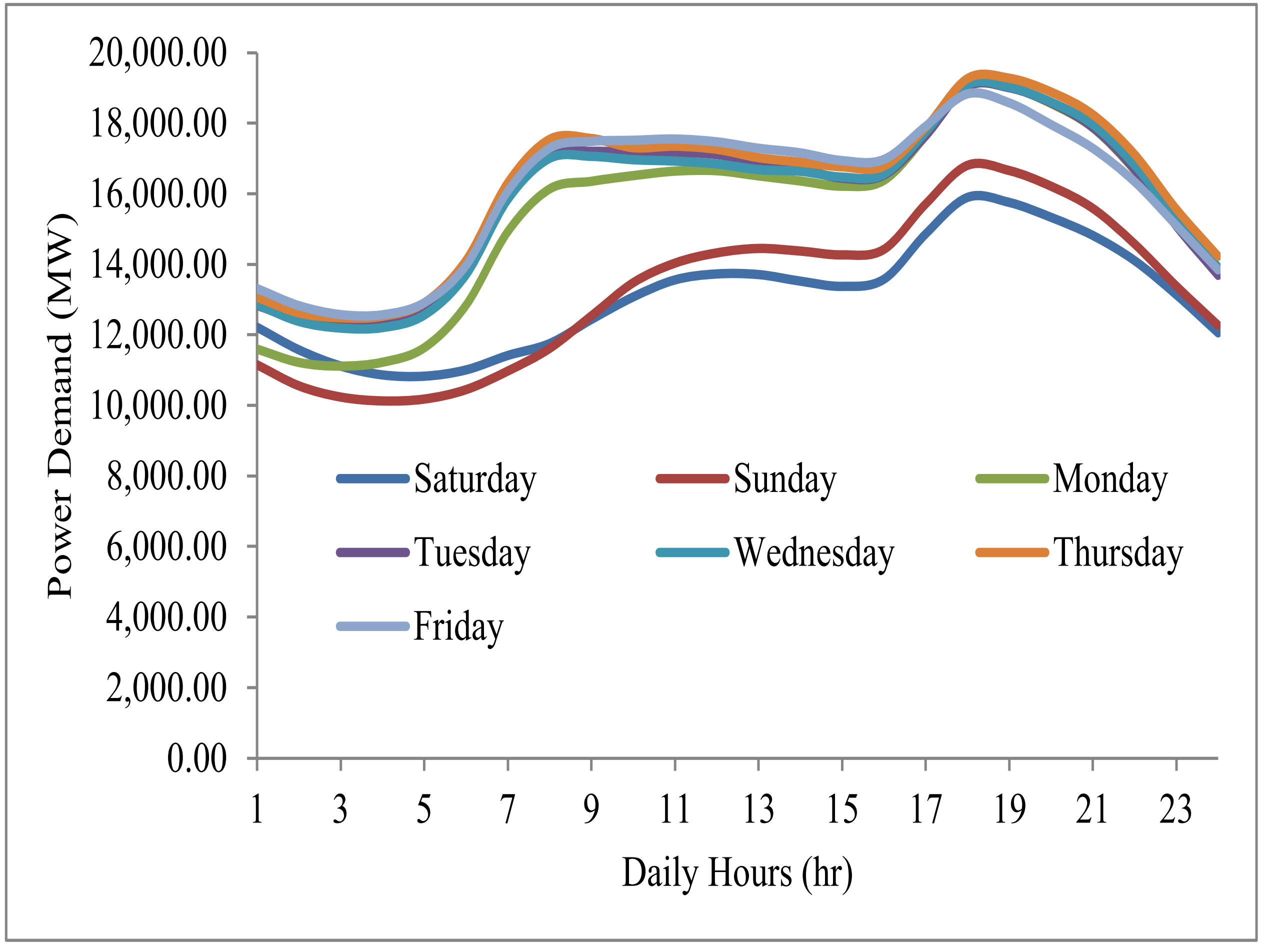
- Despite the environmental and climate change concerns as shown on the following Figure the penetration of RES into the total worldwide energy production is very slow with a total percentage of 5%.
- Worth noting however, that after 2000 there is a more rapid increase in the percentage reaching to nearly 4.5% from 2.5%.



RES Integration Issues and Solutions

Predictable Power Demand Patterns

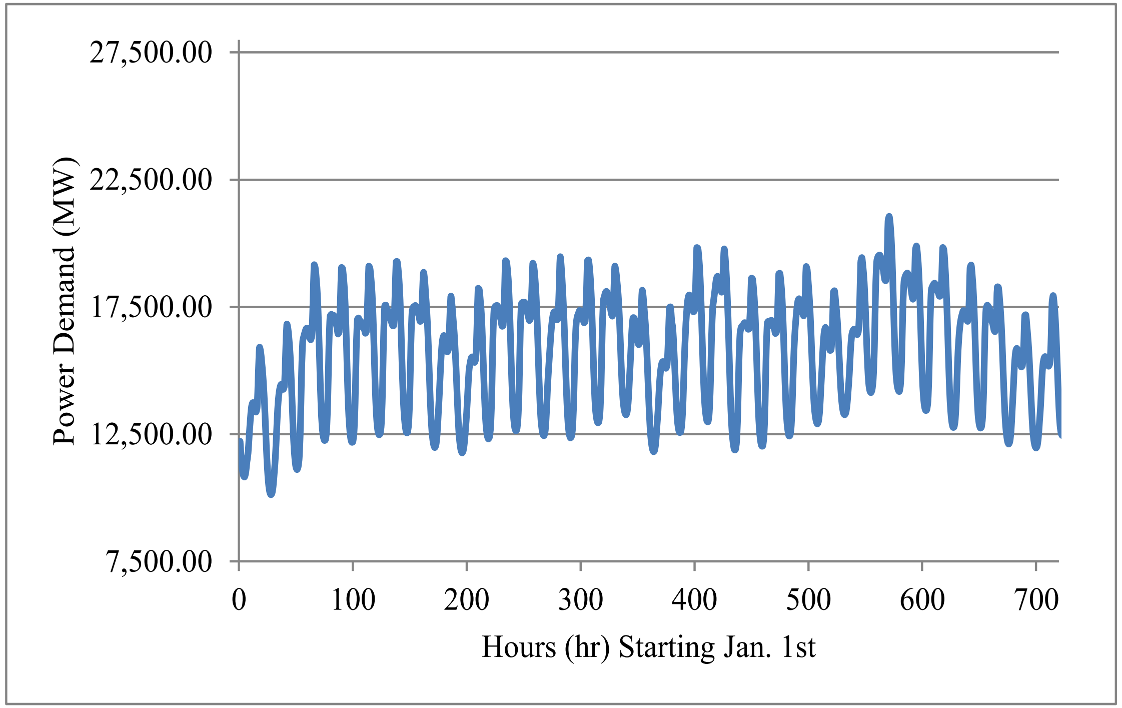
- Power demand worldwide is variable; it changes hourly, daily, weekly, monthly. It depends on weather conditions, people's habits and comfort levels. It changes from country to country. However, as shown the aforementioned patterns change in a predictable manner.
- The daily pattern presented, show that the "on-peak" hours are from 7am to 10pm whereas the off-peak hours are from 10pm to 7am.
- Also, the demand during weekends is lower as compared to the rest of the week.

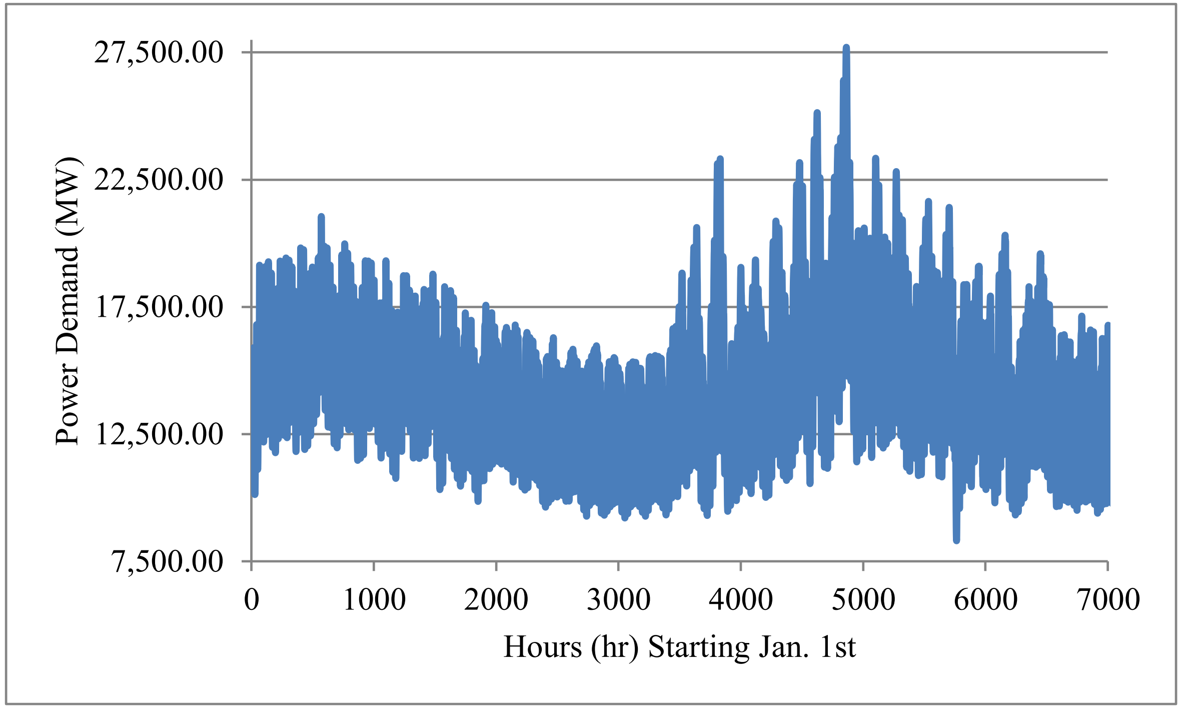


Daily Power Demand Pattern

RES Integration Issues and Solutions

Predictable Power Demand Patterns





Weekly Power Demand Pattern

Seasonal Power Demand Pattern

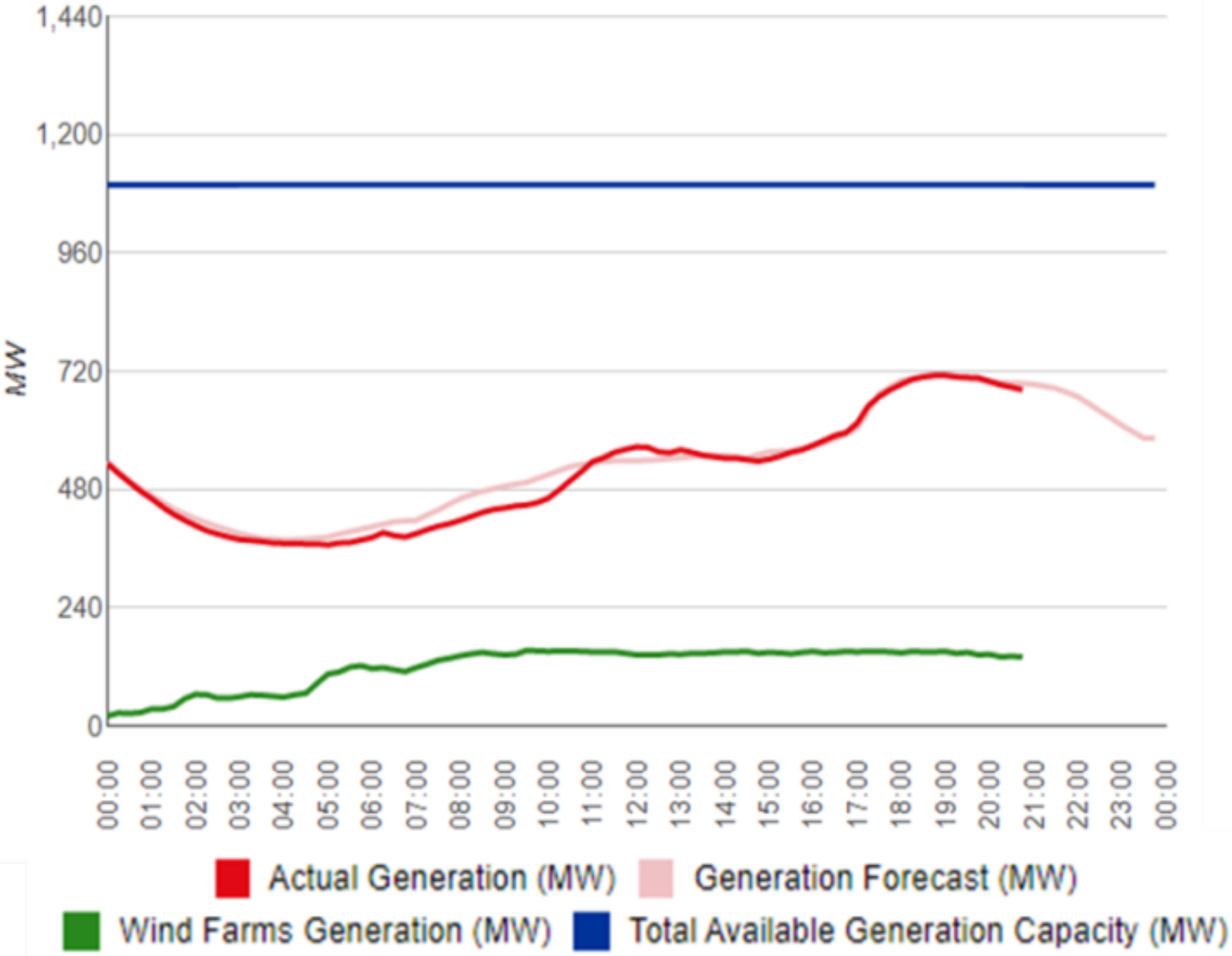
RES Integration Issues and Solutions

Predictable Power Demand Patterns

- Predictable power patterns yield to accurate power forecasts
- Conservation of Energy

$$\sum P_{Gen} = \sum P_{demand} + \sum P_{Loss}$$

- Stability
- Reliability



Cyprus System Generation

RES Integration Issues and Solutions

Reliability vs Stability

- The two most commonly used words within the electric power industry are reliability and stability. Both have become major areas of study.
- Reliability involves the “compromise” of the equipment including the electric grid. Reliability is the study of sustained outages, switchgear lockout, blown fuses and loss of service, access and integrity.
- Stability on the other hand involves the study of maintaining the power system’s (generation, transmission and distribution) harmonization with stable frequency, voltage and rotor angles.
- Reliability recovery techniques include FLISR (Fault Location, Isolation and Service Restoration).

RES Integration Issues and Solutions

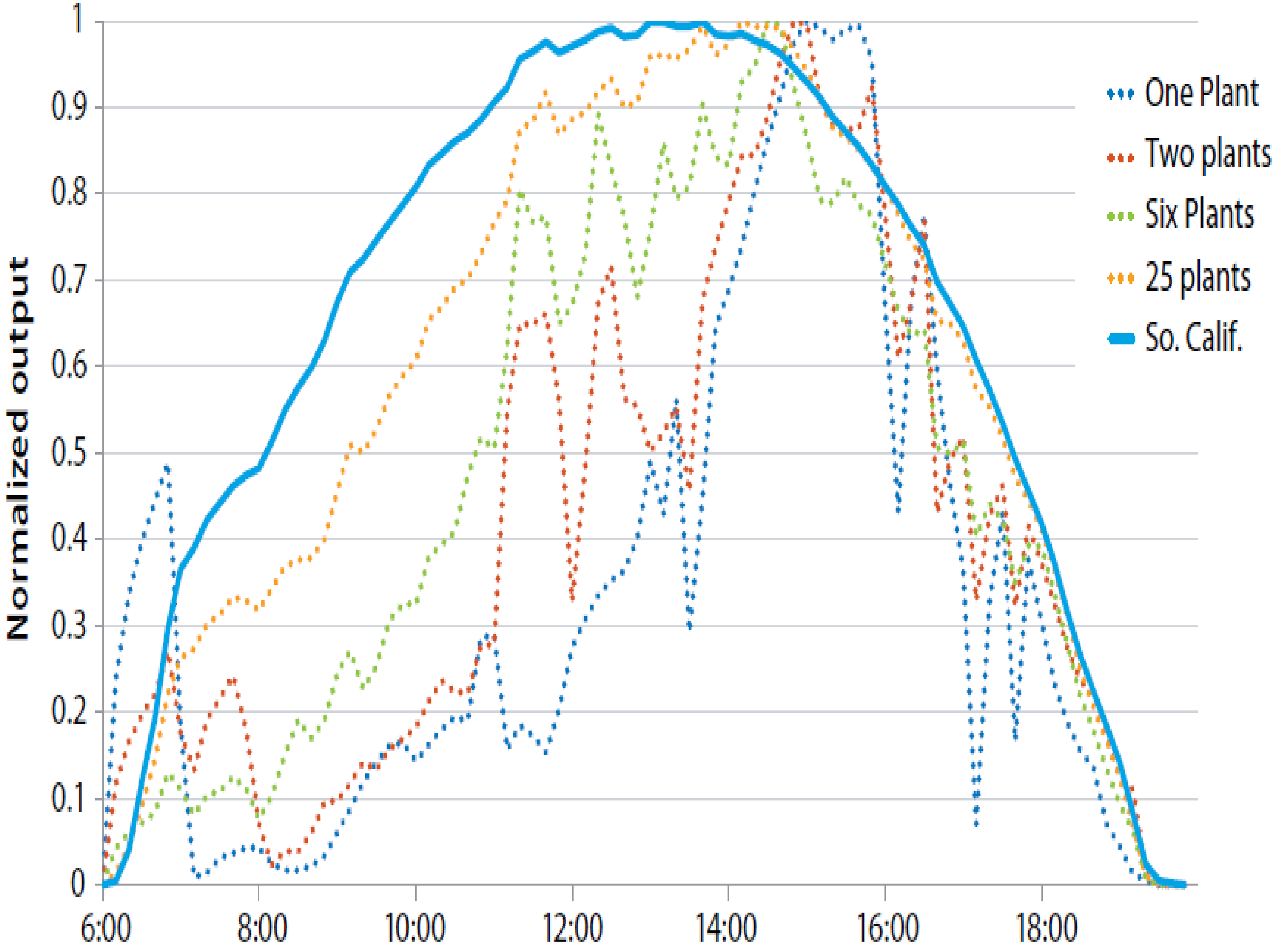
Issues

- RES into the grid presents several challenges that can affect the systems stability and reliability.
- For this reason the integration has been implemented in a controlled manner.
- Over the last several years extensive research has identified the following issues associated with RES integration into the grid.
  - Variability and Uncertainty
  - Grid Extension and Upgrade
  - Power Quality / Harmonics

RES Integration Issues and Solutions

Issue - Variability and Uncertainty

- An advantage of PV systems is that maximum generation coincides with maximum demand.
- The problem with PV generation is the shading caused by clouds which is not predictable since clouds might be passing by at different speeds.
- The PV variability is shown on the Figure.

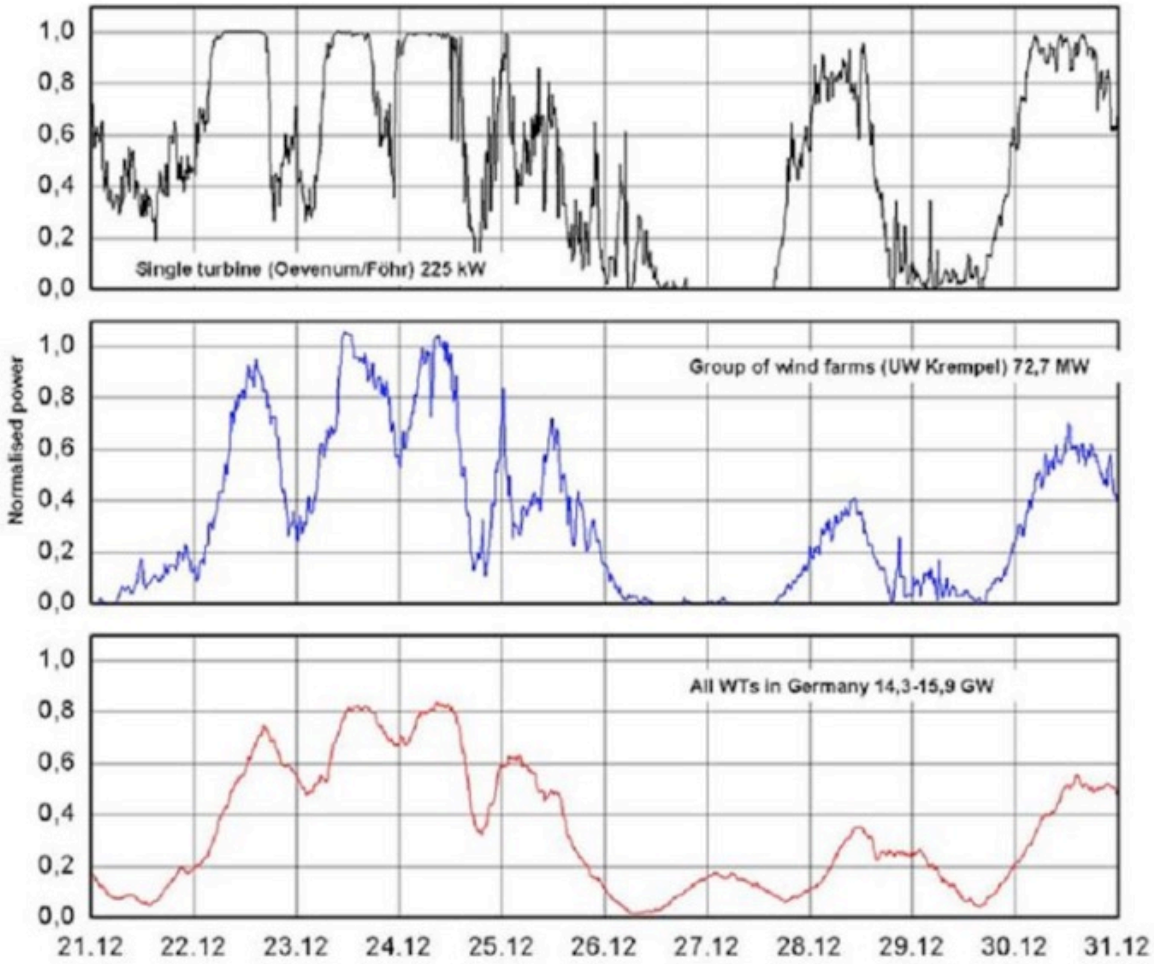


Normalized power output for increasing aggregation of PV in Southern California for a partly cloudy day [76-77]

RES Integration Issues and Solutions

Issue - Variability and Uncertainty

- Wind turbines on the other hand are not as predictable as PV systems.
- Wind turbines are subject to seasonal patterns such as winter when wind blows stronger.
- However, their daily patterns are an issue when at night when wind picks-up and the load demand is minimal.
- Furthermore, the uncertainty is exacerbated by wind gusts available throughout the year.
- A typical example of wind turbines' performance is shown on the Figure.

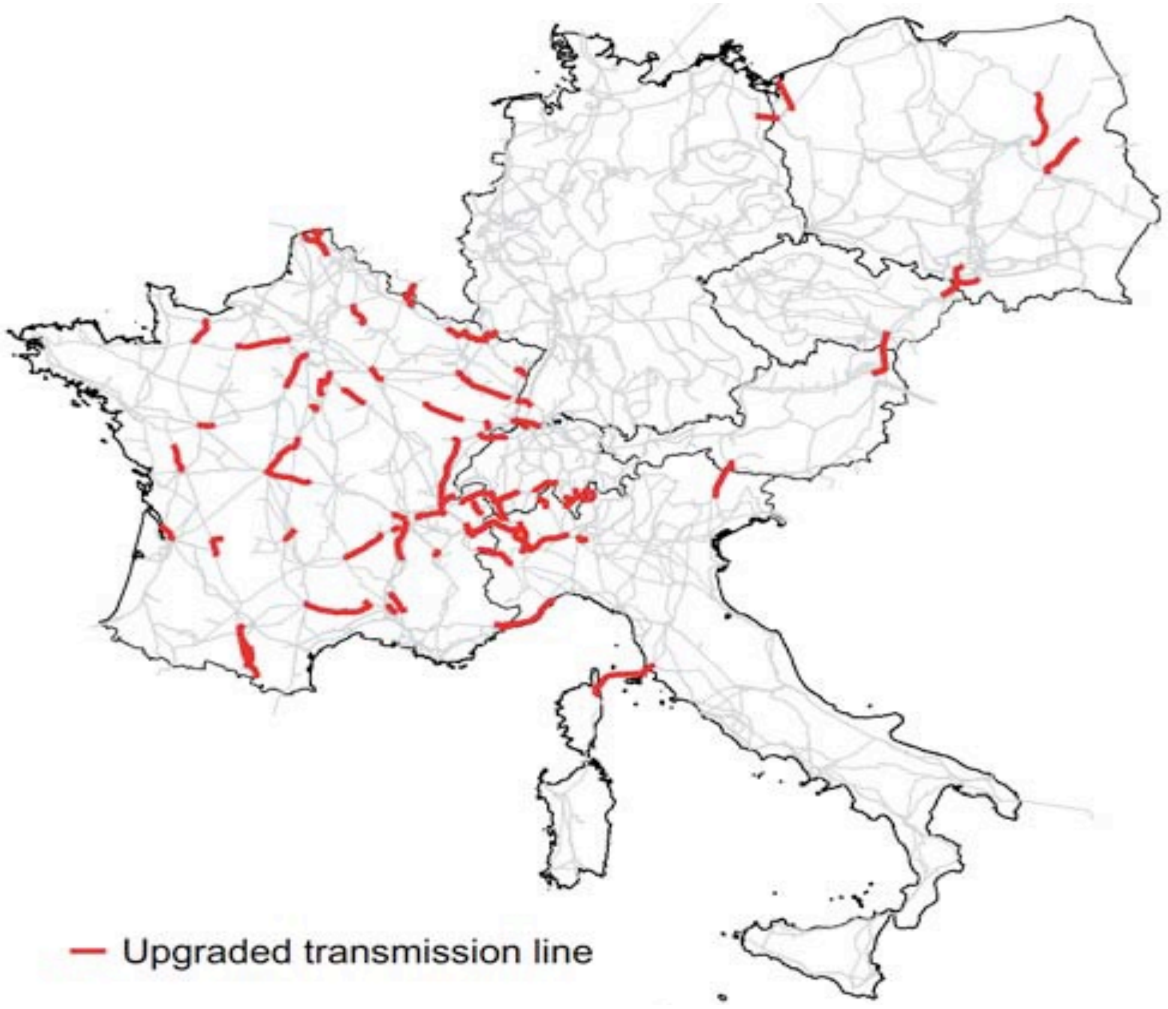


Time series of normalized power output from a single wind generator, a group of wind generators and all wind generators in Germany [21]

RES Integration Issues and Solutions

Issue - Grid Extension and Upgrade

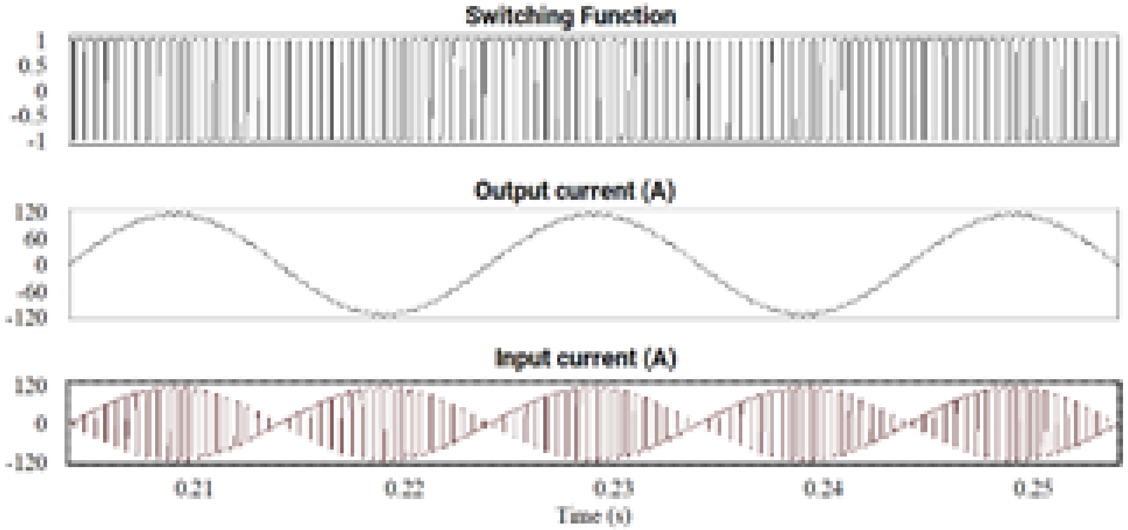
- A recent study [85] examined the optimal RES portfolio to achieve 45% renewable electricity in central Europe (France, Italy, Switzerland, Austria, Germany, Poland and the Czech Republic) by 2030.
- The results also shown on Figure 25 concluded that among the seven countries 116 transmission lines with a total length of 5000 km require reinforcement.
- However, in the case of the aforementioned developed countries this only equates to only 4% of the total length of the transmission system which might be considered insignificant.
- This might not be the case for other countries.



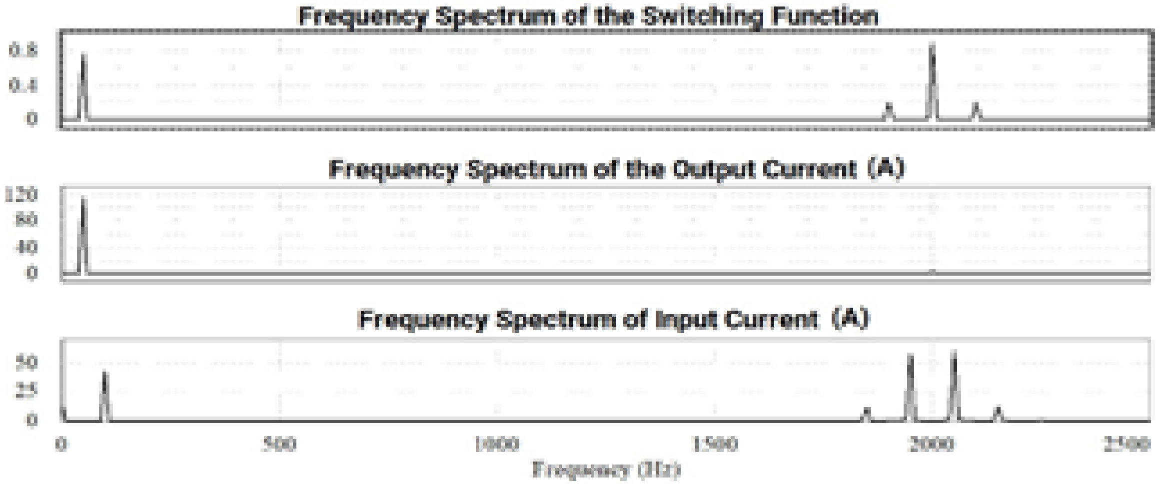
Required Upgraded Transmission Lines [85]

RES Integration Issues and Solutions

Issue – Power Quality and Harmonics



Switching Function output (peak 110A) and input (peak 110A) current waveforms of the sinusoidally modulated H-Bridge 3-Level inverter

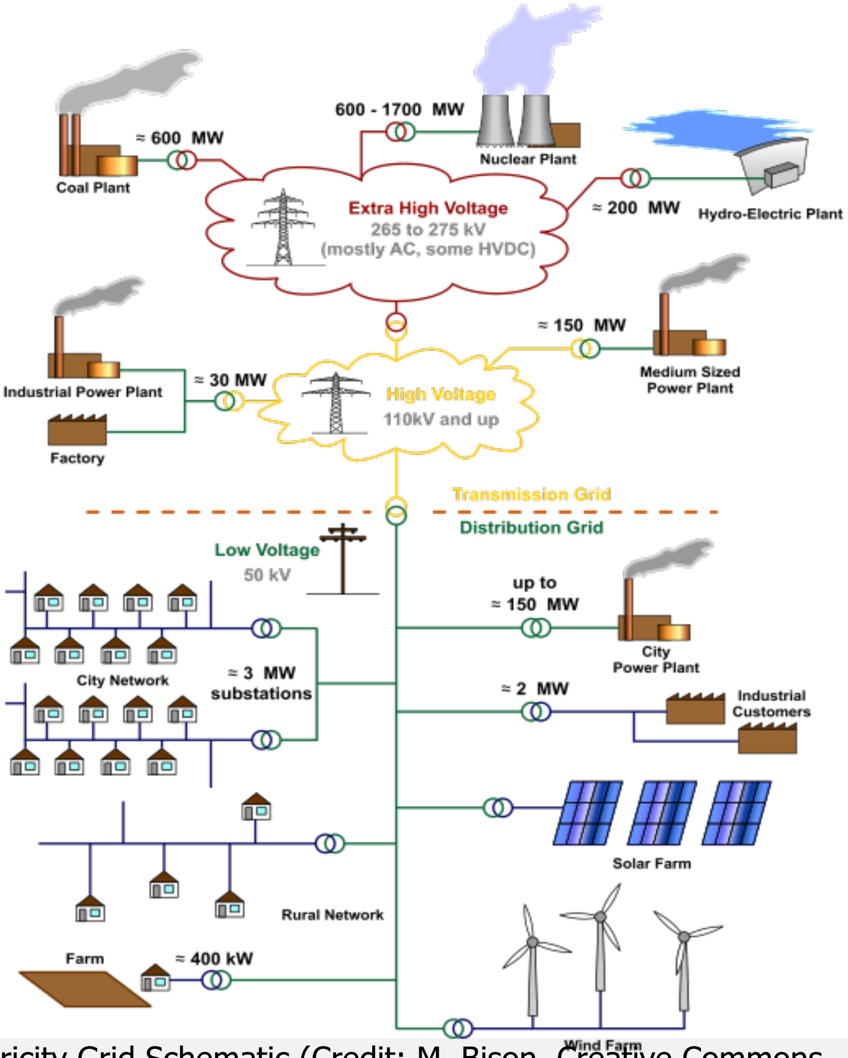


Switching Function output (peak 110A) and input (peak 110A) current waveforms of the sinusoidally modulated H-Bridge 3-Level inverter

- Harmonics are injected in the grid.
  - Affect the Total Harmonic Distortion
  - Power Factor

RES Integration Issues and Solutions

Solution - Distributed and Flexible Generation

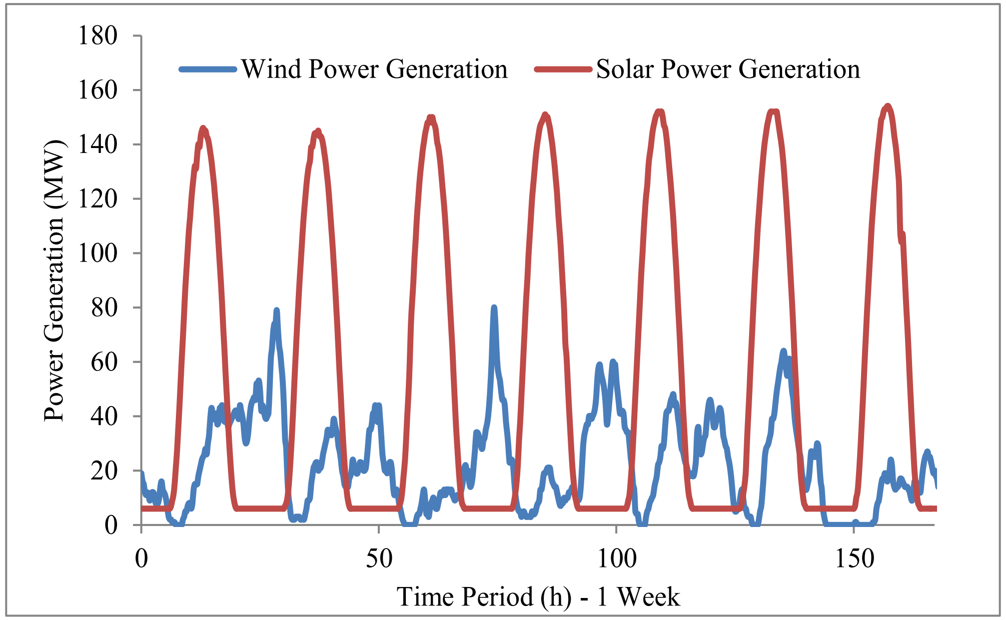


Electricity Grid Schematic (Credit: M. Bison, Creative Commons Attribution 3.0 License [101].

- Distributed Generation (DG) is a proposed technique to address the aforementioned discussed issues associated with the integration of RES to the grid.
- Distributed generation brings smaller generation technologies closer to the customer.
- These DG technologies from literature are also referred to as Distributed Generators (DG) or Distributed Energy Resources (DER) [94].
- DG technologies include small PV and wind farms (<100kWp), roof-top PV systems, small wind turbines, fuel-cell, internal combustion engines, etc

RES Integration Issues and Solutions

Solution - Extend Geographical Area



Distributed Wind and Solar Power Generation in Cyprus

○ As it has already been discussed by dispersing the wind and solar generation to a wider geographical area minimizes the impact on the grid due to variability and uncertainty.

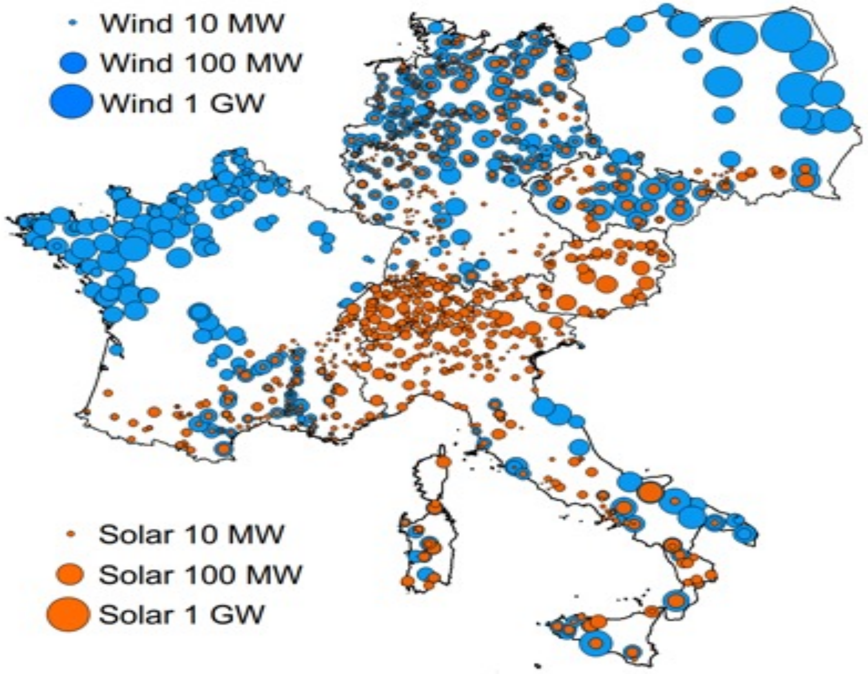
○ This is because clouds and wind fluctuations affect only portions of the plats' capacity. An example is illustrated on Figure which represents the solar and wind generation on a typical day in Cyprus.

○ It is evident that solar and wind dispersed around the island provide a smooth power generation curve.

○ Also, evident is the fact that solar peak is around noon whereas wind peak is in the afternoon and evening hours.

RES Integration Issues and Solutions

Solution - Distributed and Flexible Generation



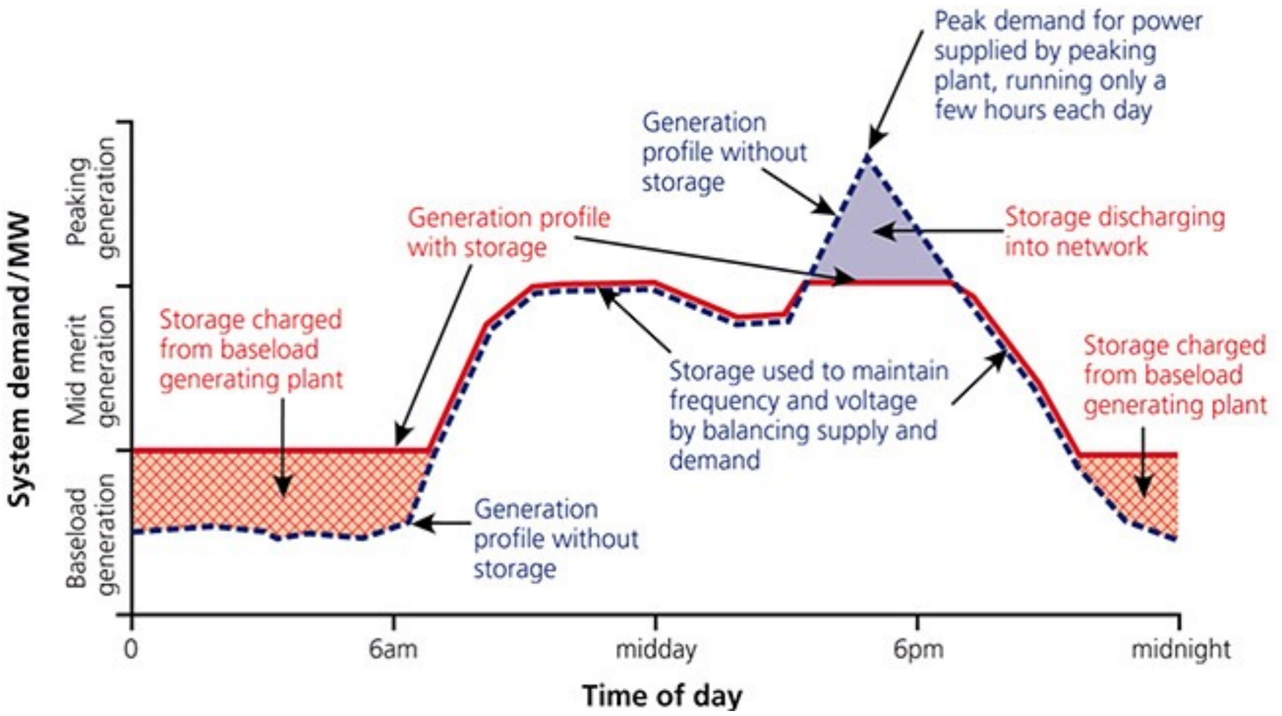
Optimal RES portfolio to achieve 45% renewable electricity in central Europe by 2030 (Credit: Dr. Reza Abhari and Energy Science Center (ESC), ETH Zurich [102])

- A recent study [85] and [102] examined the possibility of an optimal RES portfolio to achieve 45% renewable electricity in central Europe (France, Italy, Switzerland, Austria, Germany, Poland and the Czech Republic) by 2030.
- As it was suggested and presented on Figure, this is feasible by spreading the wind and solar generation to the identified locations.

RES Integration Issues and Solutions

Solution – Energy Storage

- Energy is stored when is least needed (off-peak hours) and then it is used when needed the most (peak hours).
- As illustrated storage helps to reduce the peak generation power while at the same time it helps maintain the frequency and voltage.
- The integration of energy storage to the grid requires the use of power electrics and energy management techniques and algorithms.
- List of technologies include pumped hydro, batteries, fly-wheels, super-capacitors, compressed air and hydrogen.
- Note:
  - All Energy Storage Systems have their unique technical characteristics and constraints as conventional generators.



Fundamental Idea of Energy Storage [103-108].`

RES Integration Issues and Solutions

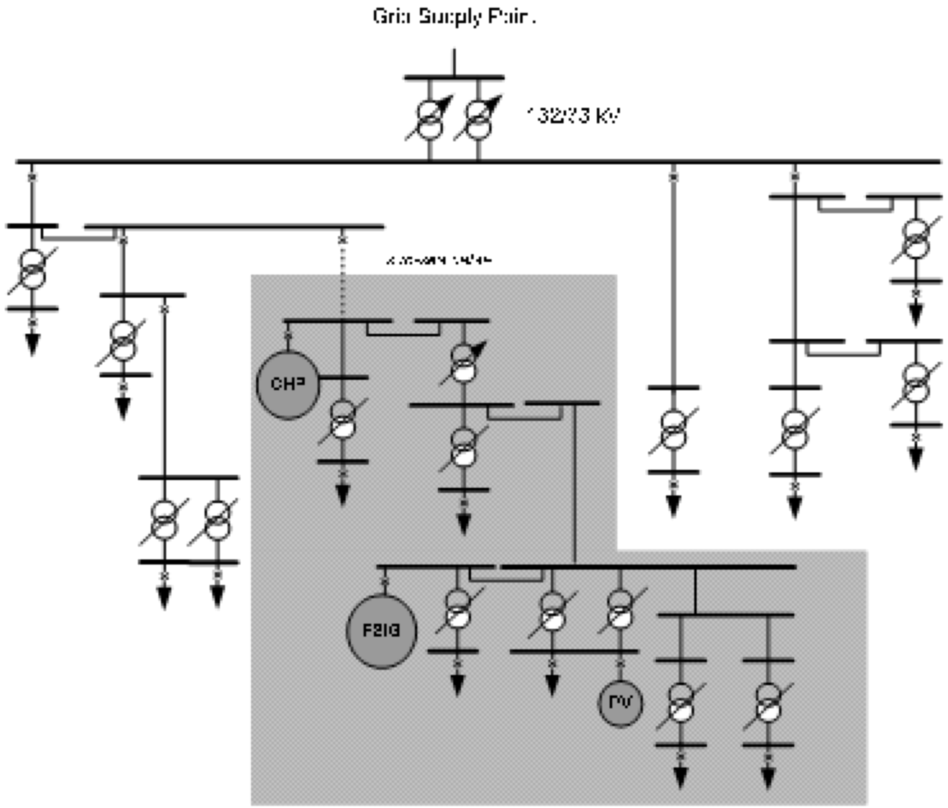
Solution – Energy Management System

- An EMS is a computerised system that helps the Transmission and Distribution System Operators (TSO and DSO respectively) to monitor, control, and optimize the network.
- Early energy management systems (EMS) developed in the 1970s were simple because the electric power industry was centralised and monopolised. The distribution network was a passive system because power flowed only in one direction; from generation to the customers. Therefore, EMS was required only on Transmission side.
- However, nowadays, with the penetration of DG the distribution network is bidirectional, allowing power to flow from customers to the network, hence more advanced EMS are required.
- The concepts for both transmission and distribution networks are the same. However, because the characteristics of transmission and distribution lines are completely different (construction, X/R ratio, phase imbalance, etc.) then an "all-purpose" EMS is not feasible.

RES Integration Issues and Solutions

Solution – The State of the System

- The Single-line diagram of the 33 kV distribution network with different types of distributed generation is presented on Figure 34.
- The system operators (TSO and DSO) are interested for the state of the system. #
- The "state" includes all the bus voltages and power angles also known as the "static state vector", as well as all the currents, power magnitudes (MW and MVAR) and directions, power line loading, etc.
- The theoretical system's state can be calculated
  - start with the power line impedances
  - form the network's admittance matrix also known as the "Jacobian Matrix"
  - use techniques such as the Newton-Raphson to solve for the parameters of the power flow equations [20-21].
  - However, this process is very time consuming.

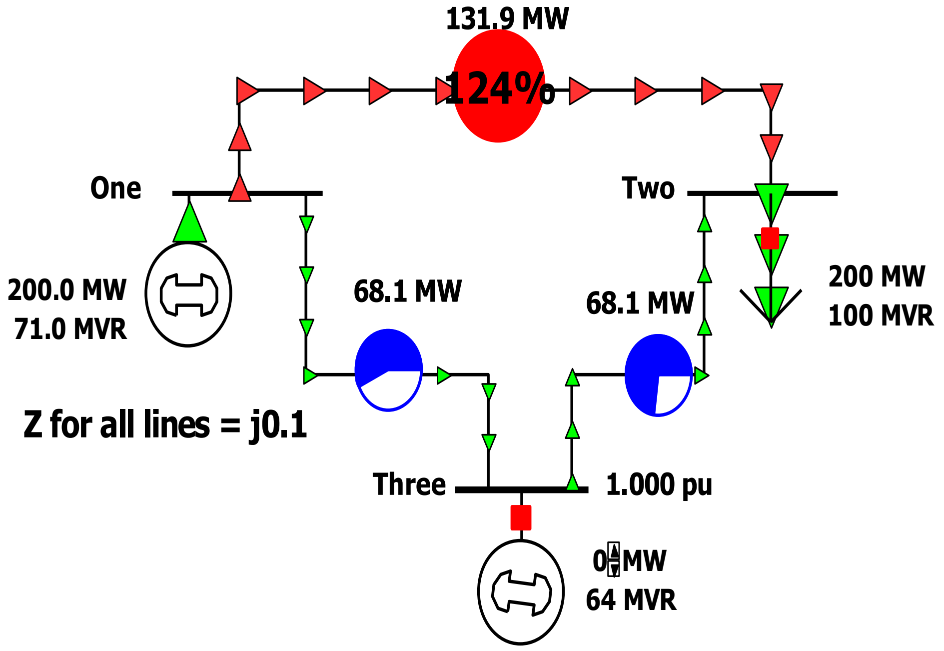


Single-line diagram of the 33 kV distribution network with different types of distributed generation

RES Integration Issues and Solutions

Solution – Computers and Simulation Software

- Computers are used for faster and accurate results using simulation software such as the PowerWorld Simulator [109].
- Using simulation software, the operators can study the systems performance and also design contingency procedures.
- Contingency procedures are counter measures to be taken to avoid line overloading, frequency and voltage collapse in the events of loss of transmission lines, generation etc.
- To illustrate a contingency situation a simple 3 bus system is analysed.
  - The initial performance of the 3 bus system with two generators and one load.
  - As shown the load demand of 200MW (real power) and 100MVAR (reactive power) is met with generator 1 supplying 200MW, 71MVAR and generator 2 only 64MVAR.
  - However, simulation results when this scenario is implemented an overload (24%) is created on the line connecting buses 1 and 2.

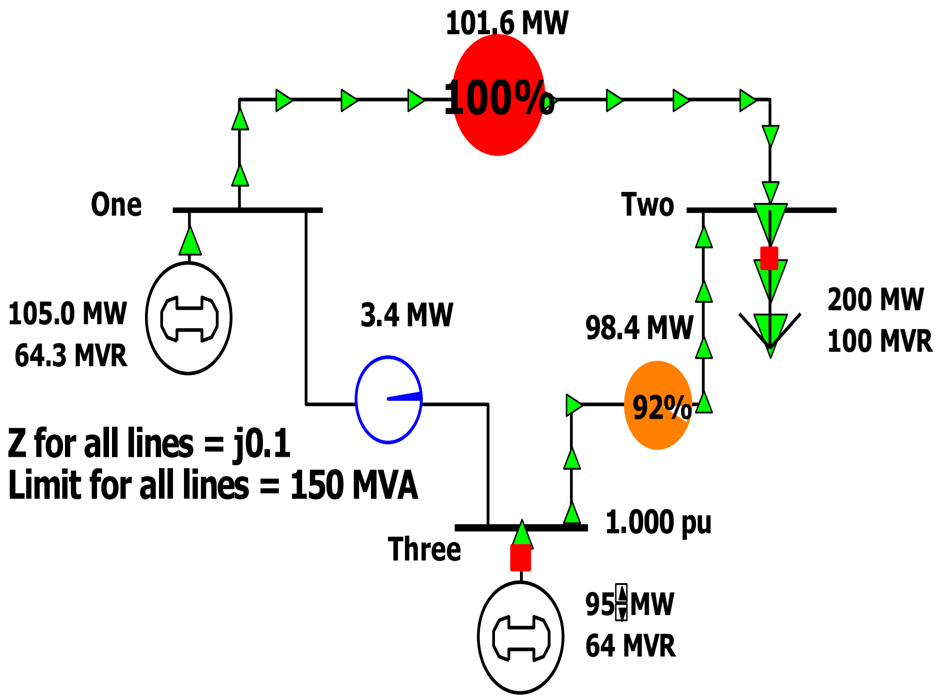


Contingency Example of a 3 Bus System using Power World Simulator (Before).
Arrows represent the power directions. When the arrows are green then the power is within limits whereas red arrows indicate a constraint violation.

RES Integration Issues and Solutions

Solution – Computers and Simulation Software

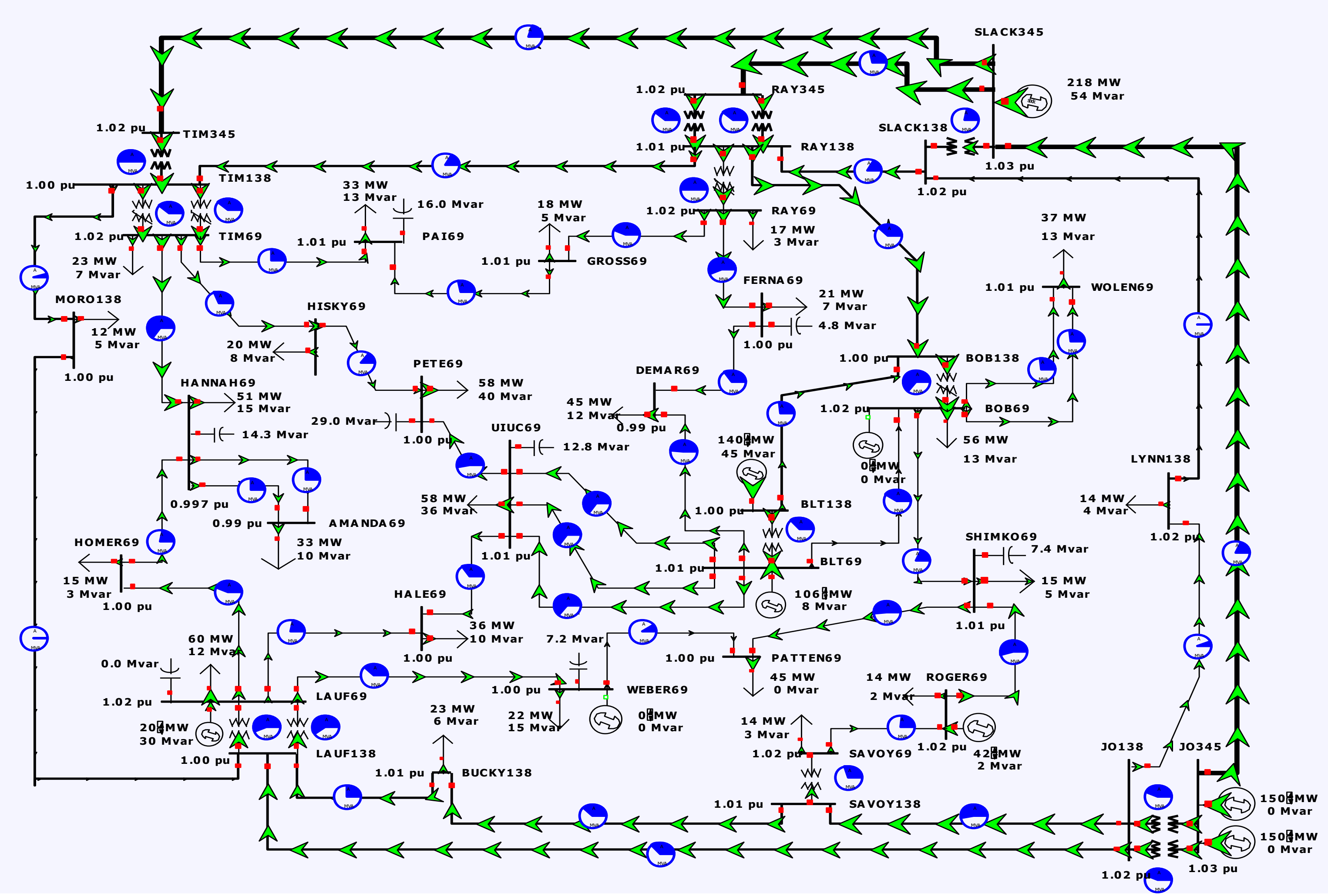
- The contingency solution to the line overload as presented is to minimise the real power supplied by generator 1 from 200MW to 105MW and increase the real power supplied by generator 2 from zero to 95MW.
- The proposed solution is not unique and it depends on the experience and skills of the operators.
- Furthermore, using the simulation software for the specific 3 bus system the simulation time to converge is less than a second.



Contingency Example of a 3 Bus System using Power World Simulator (After).
Arrows represent the power directions. When the arrows are green then the power is within limits whereas red arrows indicate a constraint violation.

RES Integration Issues and Solutions

Solution – Computers and Simulation Software



Power Flow Simulation using the Power World Simulator

- A big network with numerous busses, transformers, generators and loads using Power World Simulator.
- The initial input of the network in the software according to experience could take up to 2 hours.
- However, after that the convergence time is less than 20 seconds.
- Note: DG and RES are also included in the software package.

RES Integration Issues and Solutions

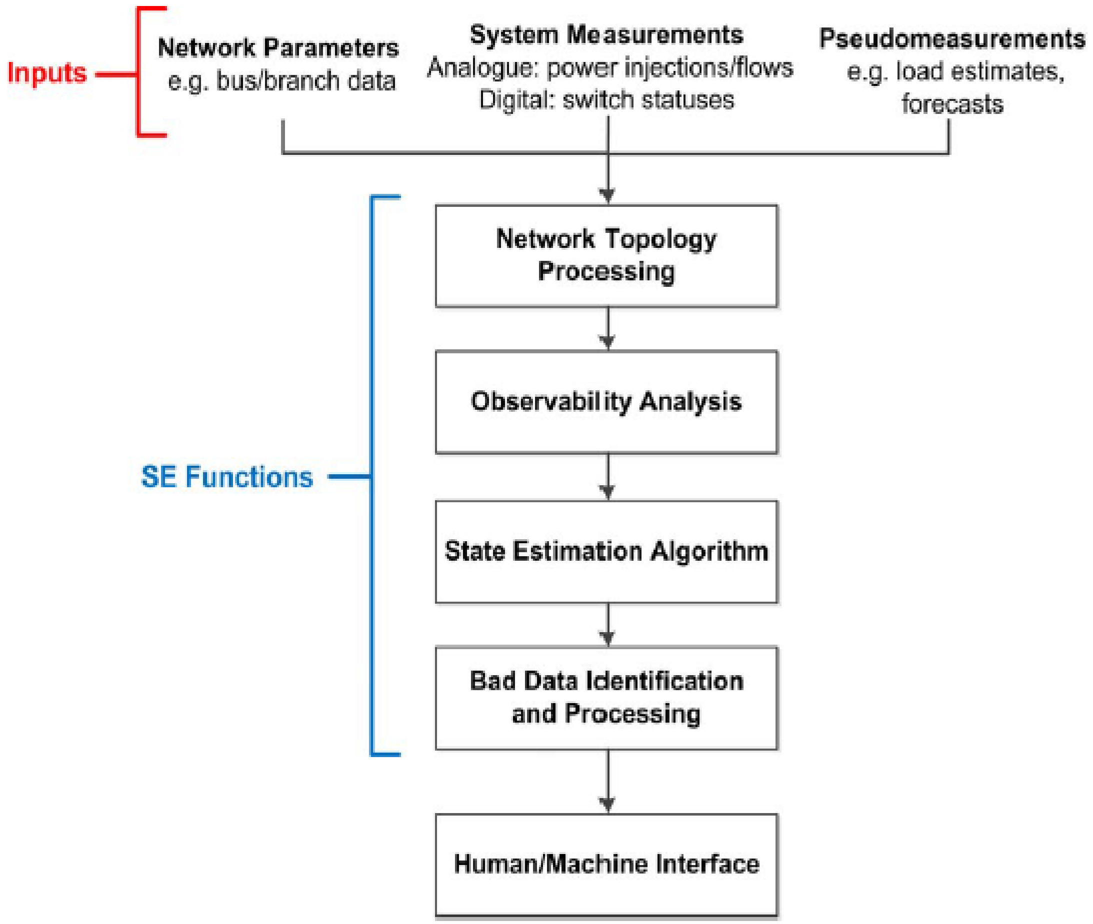
Solution – The State Estimation (ES)

- Simulation results enable the operators to have an overview of the system’s theoretical state. The actual state on the other hand requires access to system measurements which are affected by tolerance, errors, missing and corrupted data due to noise and interference; Supervisory Control and Data Acquisition (SCADA) is discussed on the next section.

- The mitigation of missing and corrupted network data is handled with the use of “State Estimation (SE)”.
  - introduced in 1968 by Fred Schweppe, SE was defined as a data processing algorithm offering better analysis of the electric power system with an estimate of the state by converting redundant meter readings and other available information [110-112].

RES Integration Issues and Solutions

Solution – The State Estimation (ES)

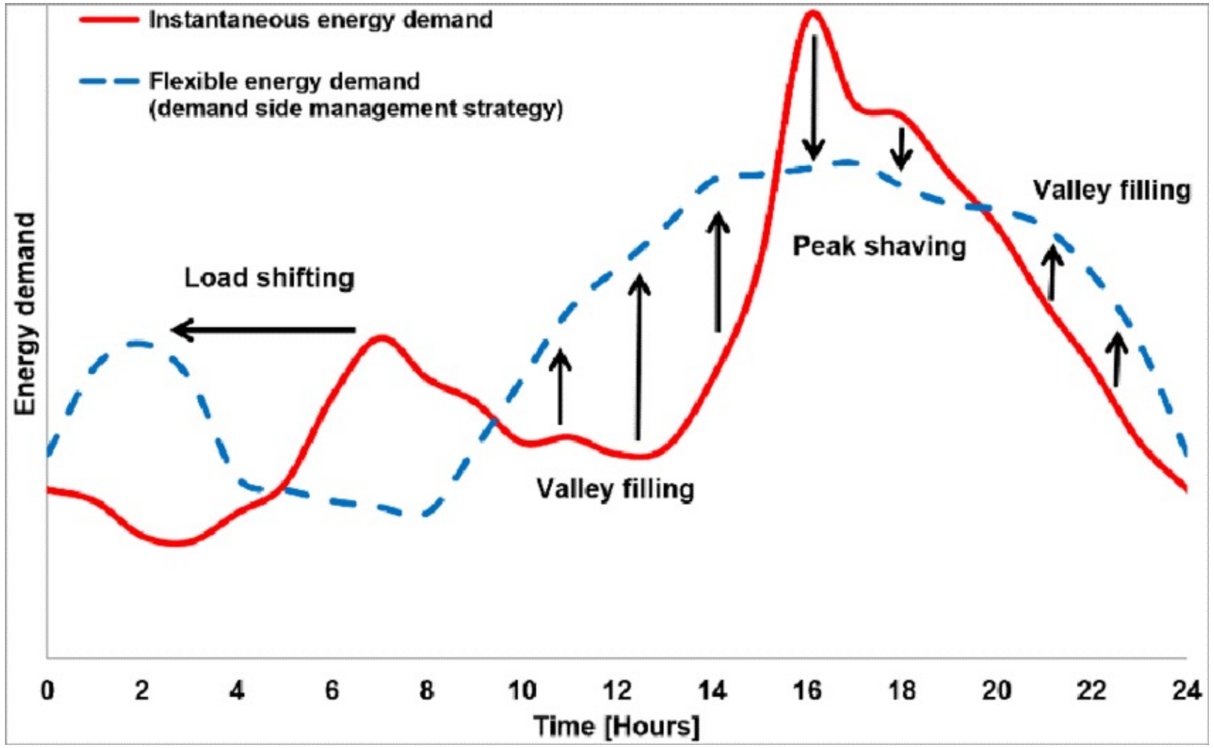


Summarised the ES Functions of ES [114]

- Hayes and Prodanovics [113-114] with the use of a block diagram summarised the functions of ES as described in literature.
- Inputs include the network parameters obtained from the construction of the network (i.e. busses, line and transformer admittances, constraints, etc), pseudo-measurements obtained from forecasting (i.e. weather conditions, load demand, RES generation, etc) and actual system measurements (i.e. dispatched power, loss of lines or generation, etc) [113-114].
- The first function identified as the Network Topology Processing is responsible for the verification and validation of the given network parameters (i.e. ensuring that the network model is update).
- The second identified function is the Observability Analysis which determines that there is enough data (measurements) for the SE. In the event that data is inadequate then pseudo-measurements are provided. Data adequacy depends on the Jacobian Matrix [115].
- The third proposed SE algorithm uses the verified and validated data from the previous functions and identifies the solution for the system’s state that best fits the systems criteria and constraints.
- The fourth and last identified function is the Bad Data Processing (BDP) which identified and removes data affected by errors and noise.

RES Integration Issues and Solutions

Solution – Demand Side Energy Management



Demand Side Management and Energy Flexibility (Available via license CC BY 3.0 [118])

Energy management can also be applied on the demand side providing flexibility to the electric power system.

Flexibility is defined by the industry as the ability to adapt to dynamic and changing conditions such as the ability to balance the supply and demand by time periods ranging from hours to seconds.

Demand side energy management aims at smoothing of the steep slopes of instantaneous demand as presented on Figure 39; i.e. load shifting, valley shifting and peak shaving are some of the techniques used to provide system flexibility.

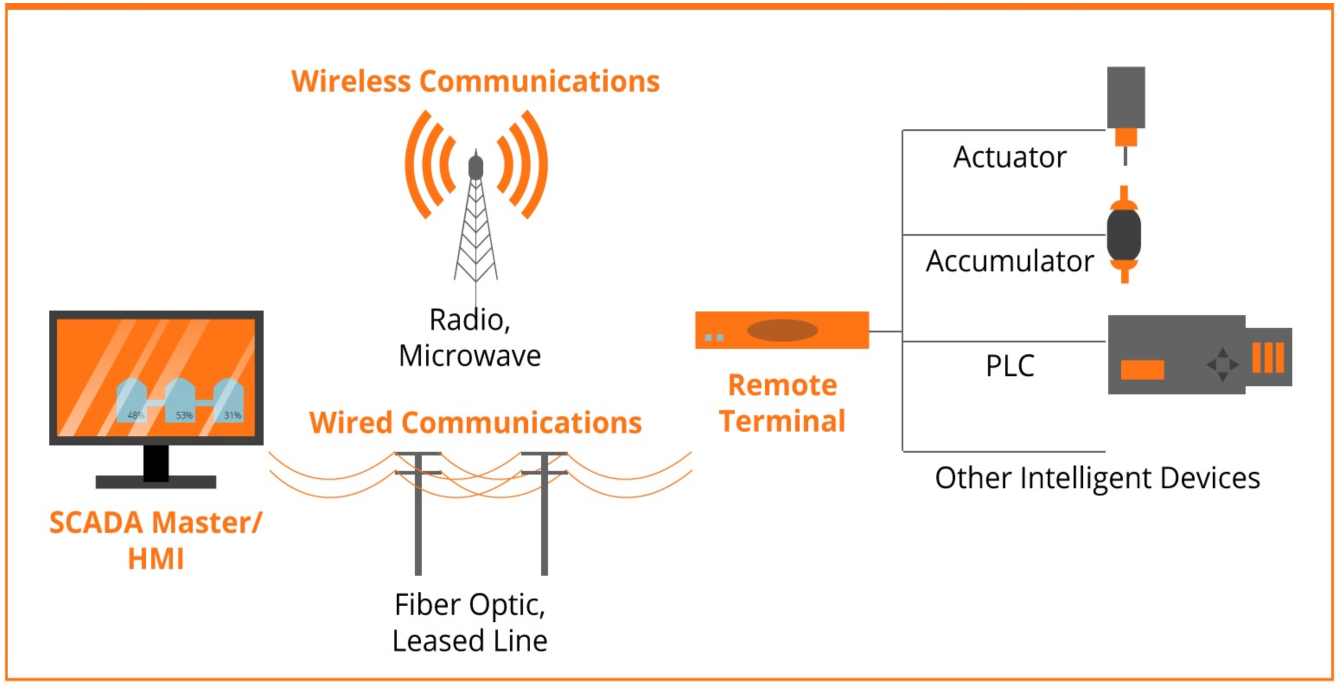
A lot of research focuses on residential buildings to shift loads (heating, cooling, energy storage charging, etc) from on-peak hours towards off-peak hours using economic benefits and incentives [118-119].

Additional areas of study includes planning and scheduling by employing conventional [120-121] and computational [122-123] optimization techniques as well as load shedding and peak shaving techniques [124-126].

RES Integration Issues and Solutions

Solution – Supervisory Control and Data Acquisition (SCADA)

- Energy Management Systems depend on the Supervisory Control and Data Acquisition (SCADA) systems. SCADA has two major functions.
  - First is to retrieve data and alarms from remote sites.
  - Second is to enable control of devices or machines at remote sites [131].
- The human machine interface (HMI) is connected to the remote terminal via wireless and wired communication methods.
- Wired technologies include Power Line Communications (PLC), fiber-optics and Digital Subscriber Line (DSL).
- Wireless technologies on the other hand include but are not limited to World Wide Interoperability for Microwave Access (WiMAX), Universal Mobile Telecommunications System (UMTS), Long-Term Evolution (LTE), Wi-Fi and Wireless Personal Area Network (WPAN).

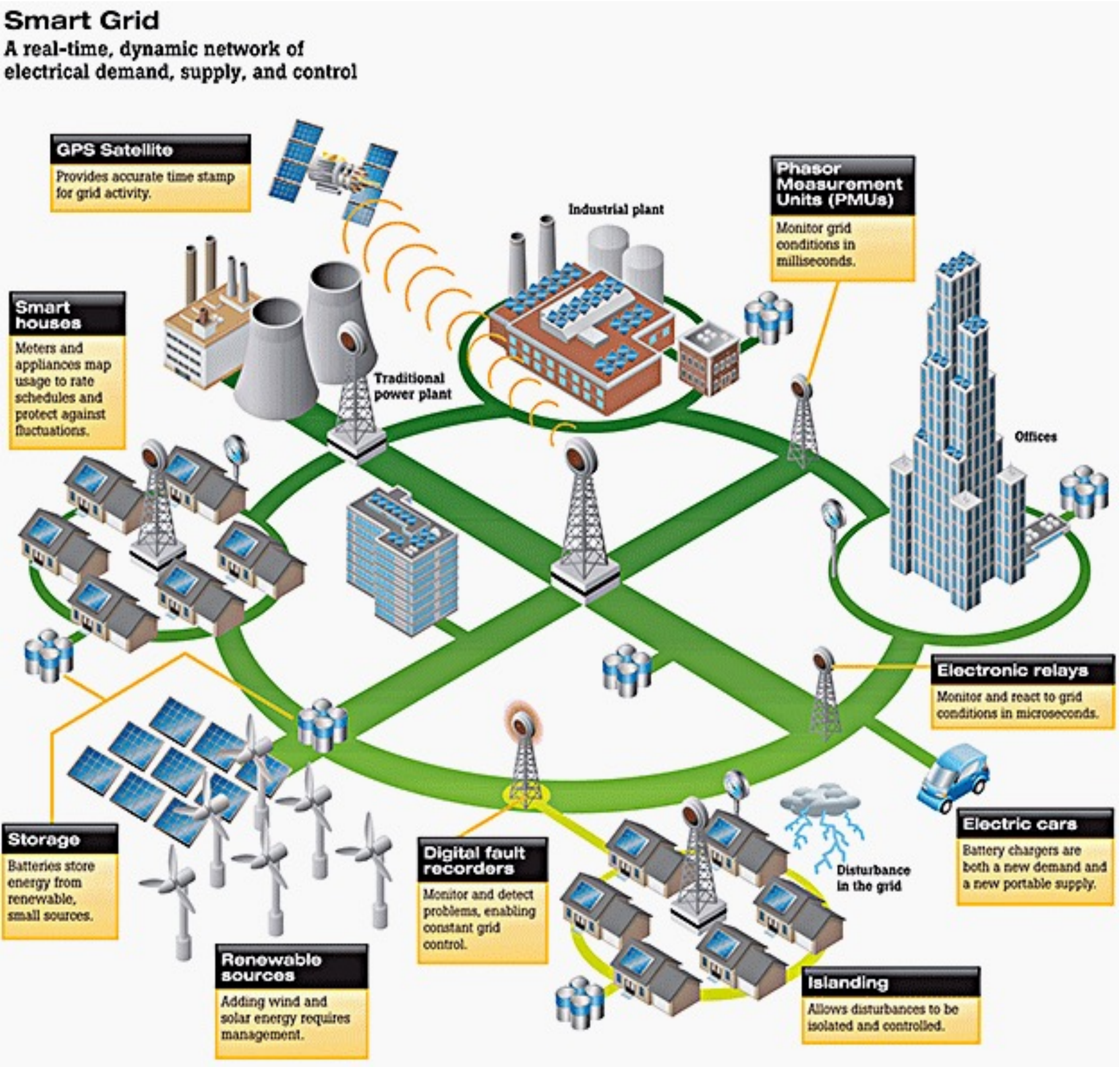


General SCADA Layout (Credit: Deramsey, Wikimedia Commons author (GNU Free Documentation License - public domain) [132])

The Smart Grid

Present and Future

- ***Today's grid is considered as one of the biggest an most complex man-made system [143].***
- Utilityproducts.com and Mr Blaza [144] nicely summarise today's smart grid as "a real-time dynamic network of electrical demand, supply and control" and visualise it as presented.
- DG and RES closer to the customer and multiple storage systems for higher flexibility (i.e. load shifting and peak shaving), smart houses with small pv roof top systems and electric cars.
- Furthermore, the presence of digital fault recorders to monitor and detect problems and islanding for isolating the disturbances on smaller geographical areas thus affecting smaller number of customers.
- GPS for more accurate time stamp so that devices such as Phasor Measurement Units (PMU) are able to monitor the grid's state in milli-second time intervals.
- ***Energy Storage Systems are distributed along the entire network.***



SMART GRID – A real-time dynamic network of electrical demand, supply and control (Photo Credit: David Blaza and utilityproducts.com [144] using Written License Consent)

- The aim of Section I was to introduce the student to the main challenges of the electric power industry and show how energy storage is a feasible solution.
- As demonstrated Energy Storage could be used to improve:
  - the grid's stability and reliability.
  - Energy Management
    - *Peak Shaving*
    - *Load Shifting*
  - Optimization and Planning
    - *Economic Dispatch*
    - *Minimum Production Cost*
  - etc

Summary

Energy Storage Systems are of vital importance for the Smart Grid

Thank You

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Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

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Dr Stelios Ioannou

Dr Marios Raspopoulos

Introduction to Renewable Energy

Lecture 11: Energy Storage (2/2)

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

Section Outline

Energy Storage is divided into two main Sections.

Section I introduced the main challenges of the electric power industry and demonstrated various solutions including the importance of Energy Storage Systems for the Smart Grid.

The aim of Section II is to introduce the students with the various energy storage systems (technology overview) and their technical characteristics (performance metrics). Technologies under consideration include Batteries, Fuel Cells, Super-Capacitors, Hybrids (Battery and Super-Capacitor Combined), Pumped Storage Hydropower, Flywheels and Compressed Air Energy Systems. The advantages and disadvantages of all technologies are then compared and discussed.

Section II

Energy Storage Systems

Technology Overview and Performance Metrics

This week’s topics (Section II)

- Review
    - Electric Grid Challenges and Solutions
- Batteries
    - Technology Overview
    - Lithium Batteries
    - Primary Lithium Batteries
    - Scaled Up Secondary Lithium Ion Batteries
    - Performance Metrics
- Fuel Cells
    - Technology Overview
    - Performance Metrics
- Super-Capacitors
    - Technology Overview
- Battery and Super-Capacitor Combination
- Pumped Storage Hydropower
    - Technology Overview
- Flywheel Energy Storage Systems
    - Technology Overview
- Compressed Air Energy Systems
    - Technology Overview
- Discussion and Conclusions

Review

The Electric Power Grid

- The Goals
  - The highest reliability standards
  - The lowest operation cost
  - The minimum environmental impacts

Review

Reliability through Adequacy and Security

- Generation capacity must be greater than load
- Transmission must not be overloaded
- Voltages must be within limits
- Must be able to withstand loss of generator
- Must be able to withstand loss of transmission line
- Must not lose stability during short-circuit

Review

Reliability through Adequacy and Security

- Generation capacity must be greater than load
- Transmission must not be overloaded
- Voltages must be within limits
- Must be able to withstand loss of generator
- Must be able to withstand loss of transmission line
- Must not lose stability during short-circuit

- **Is this goal feasible?**

Review

Reliability through Adequacy and Security

- Generation capacity must be greater than load
- Transmission must not be overloaded
- Voltages must be within limits
- Must be able to withstand loss of generator
- Must be able to withstand loss of transmission line
- Must not lose stability during short-circuit

- **Is this goal feasible?**
  - Yes with Big Power Plants

Review

Big Power Plants

- Improve Reliability
- Lower the Production Costs

Review

Big Power Plants

- Improve Reliability
- Lower the Production Costs
- HOWEVER
  - Environmental Impact

Review

Big Power Plants

- ○ Improve Reliability
- ○ Lower the Production Costs
- ○ HOWEVER
  - Environmental Impact
    - *Emissions*

The two coal-fired power plants of the Crystal River North Steam Complex in Crystal River, Florida, (Credit: John Bradley (Ebyabe), Wikimedia Commons author (GNU Free Documentation License - public domain) [31])

Review

Big Power Plants

- ○ Improve Reliability
- ○ Lower the Production Costs
- ○ HOWEVER
  - Environmental Impact
    - *Emissions*
    - *Landscape footprint*

The two coal-fired power plants of the Crystal River North Steam Complex in Crystal River, Florida, (Credit: John Bradley (Ebyabe), Wikimedia Commons author (GNU Free Documentation License - public domain) [31])

Close View of a 500kV Lines, Southern California Edison's Path 26 (Credit: Raumfahrt Hauptfokus (Henristosch), Wikimedia Commons author (GNU Free Documentation License - public domain) [33])

Review

Solutions

○ Clean the Emissions

- Filters and Chemical Treatments

○ Distributed Generation

- Smaller generation units closer to the customer (demand)

○ Clean / Green Generation (no-emissions)

- Renewable Energy Sources

Review

Solutions

- Clean the Emissions
  - Filters and Chemical Treatments
- Distributed Generation
  - Smaller generation units closer to the customer (demand)
- Clean / Green Generation (no-emissions)
  - Renewable Energy Sources
- In a perfect world (Utopia)
  - Problem is Solved

Review

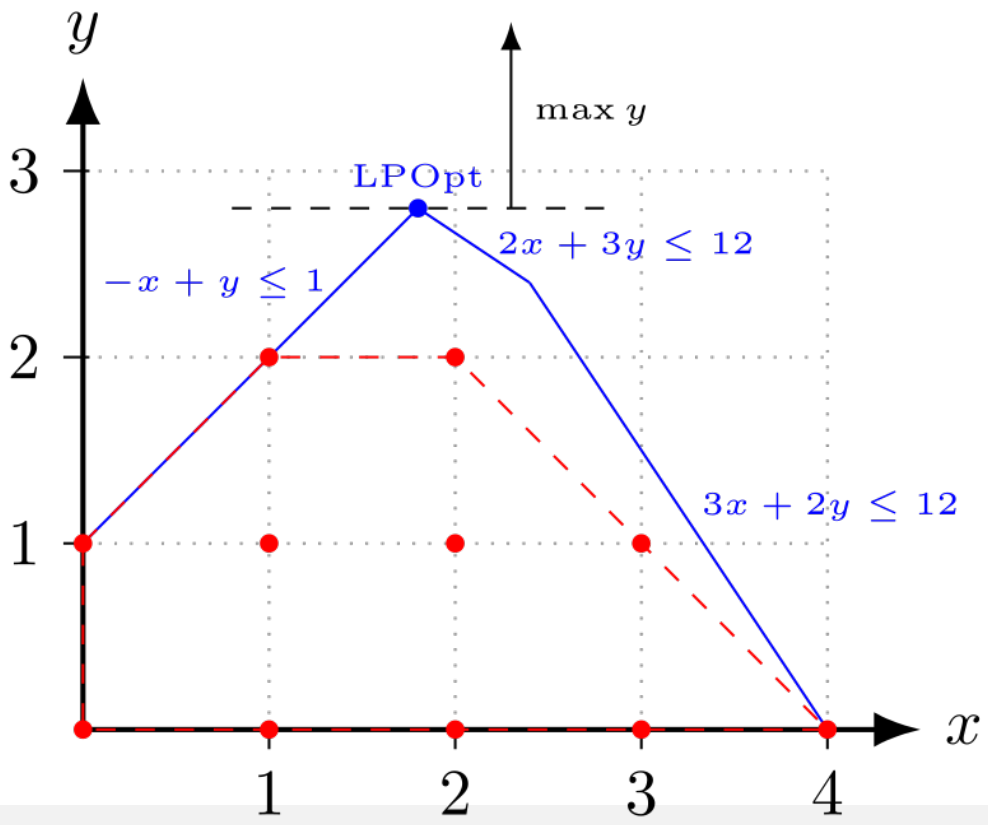
Solutions

- ○ Clean the Emissions
  - Filters and Chemical Treatments
- ○ Distributed Generation
  - Smaller generation units closer to the customer (demand)
- ○ Clean / Green Generation (no-emissions)
  - Renewable Energy Sources
- ○ In a perfect world (Utopia)
  - Problem is Solved
- ○ In real-world
  - All these solutions increase the production costs

Review

Electric Power

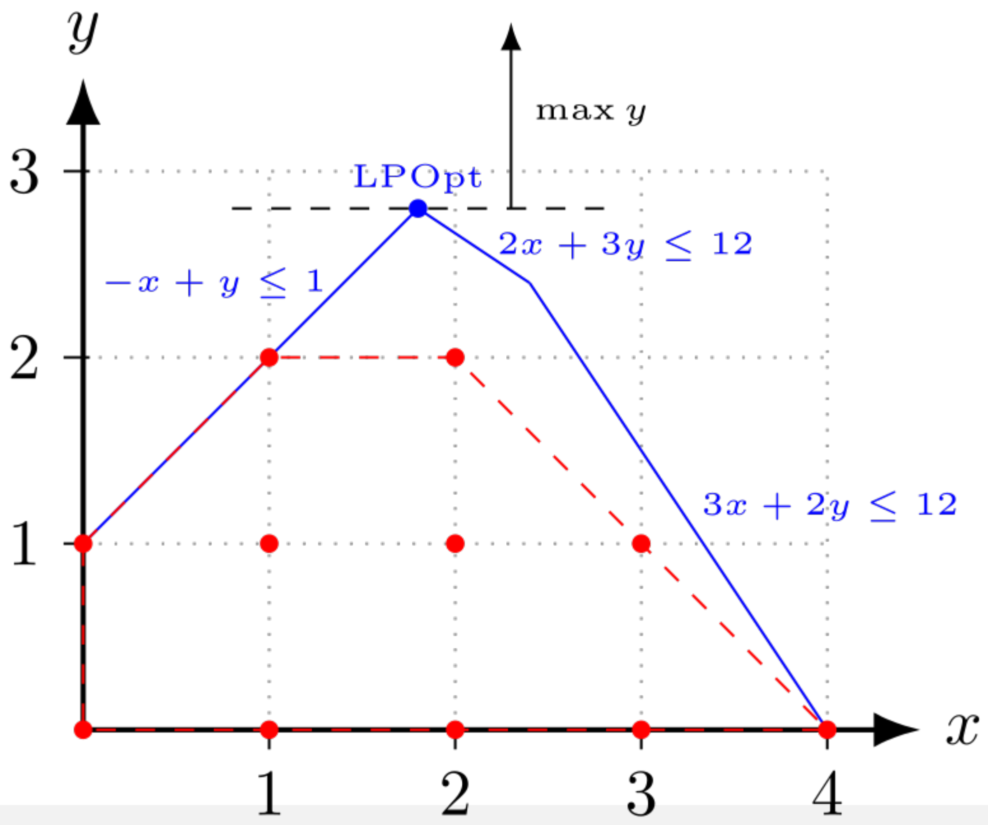
- Is an Optimization Problem with Constraints
  - With feasible and non-feasible Solutions



Review

Electric Power

- Is an Optimization Problem with Constraints
  - With feasible and non-feasible Solutions



- A balance needs to be achieved between the Goals
  - The highest reliability standards
  - The lowest operation cost
  - The minimum environmental impacts

The Smart Grid

Present and Future

- ***Today's grid is considered as one of the biggest an most complex man-made system [143].***
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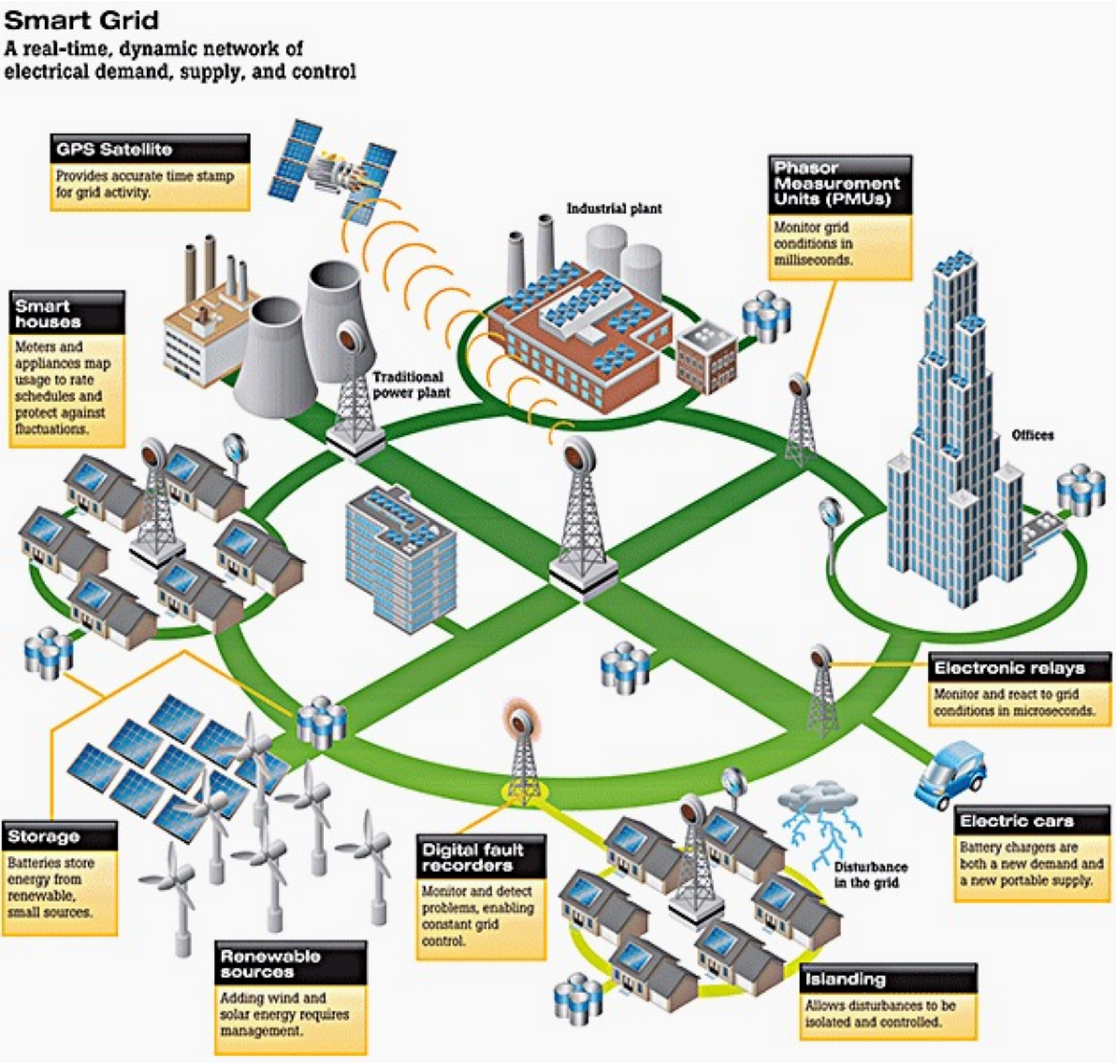

Smart Grid
A real-time, dynamic network of electrical demand, supply, and control

GPS Satellite
Provides accurate time stamp for grid activity.

Phasor Measurement Units (PMUs)
Monitor grid conditions in milliseconds.

Smart houses
Meters and appliances map usage to rate schedules and protect against fluctuations.

Electronic relays
Monitor and react to grid conditions in microseconds.

Electric cars
Battery chargers are both a new demand and a new portable supply.

Storage
Batteries store energy from renewable, small sources.

Renewable sources
Adding wind and solar energy requires management.

Digital fault recorders
Monitor and detect problems, enabling constant grid control.

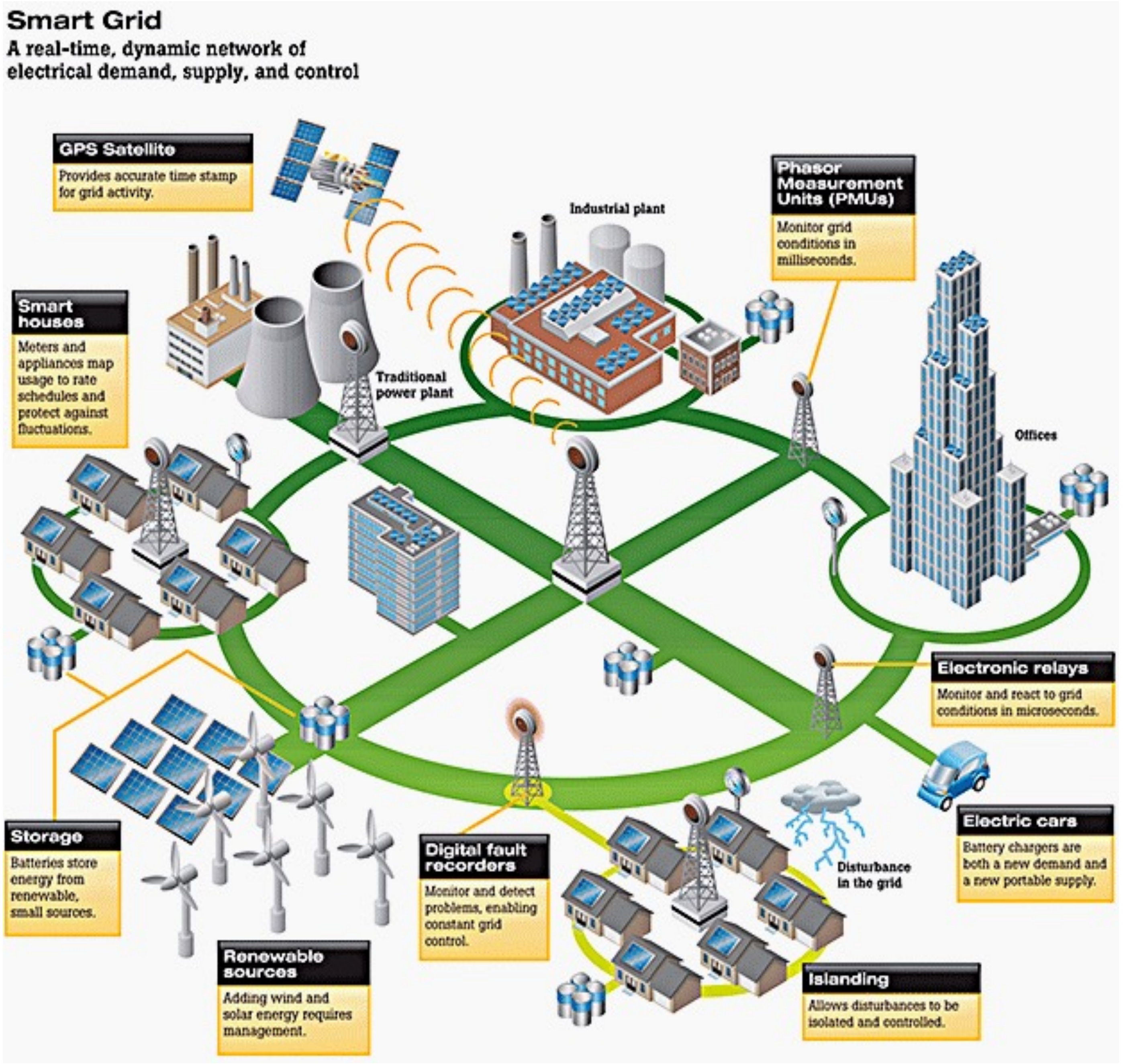
Islanding
Allows disturbances to be isolated and controlled.

SMART GRID – A real-time dynamic network of electrical demand, supply and control (Photo Credit: David Blaza and utilityproducts.com [144] using Written License Consent)

The Smart Grid

The Role of Energy Storage Systems

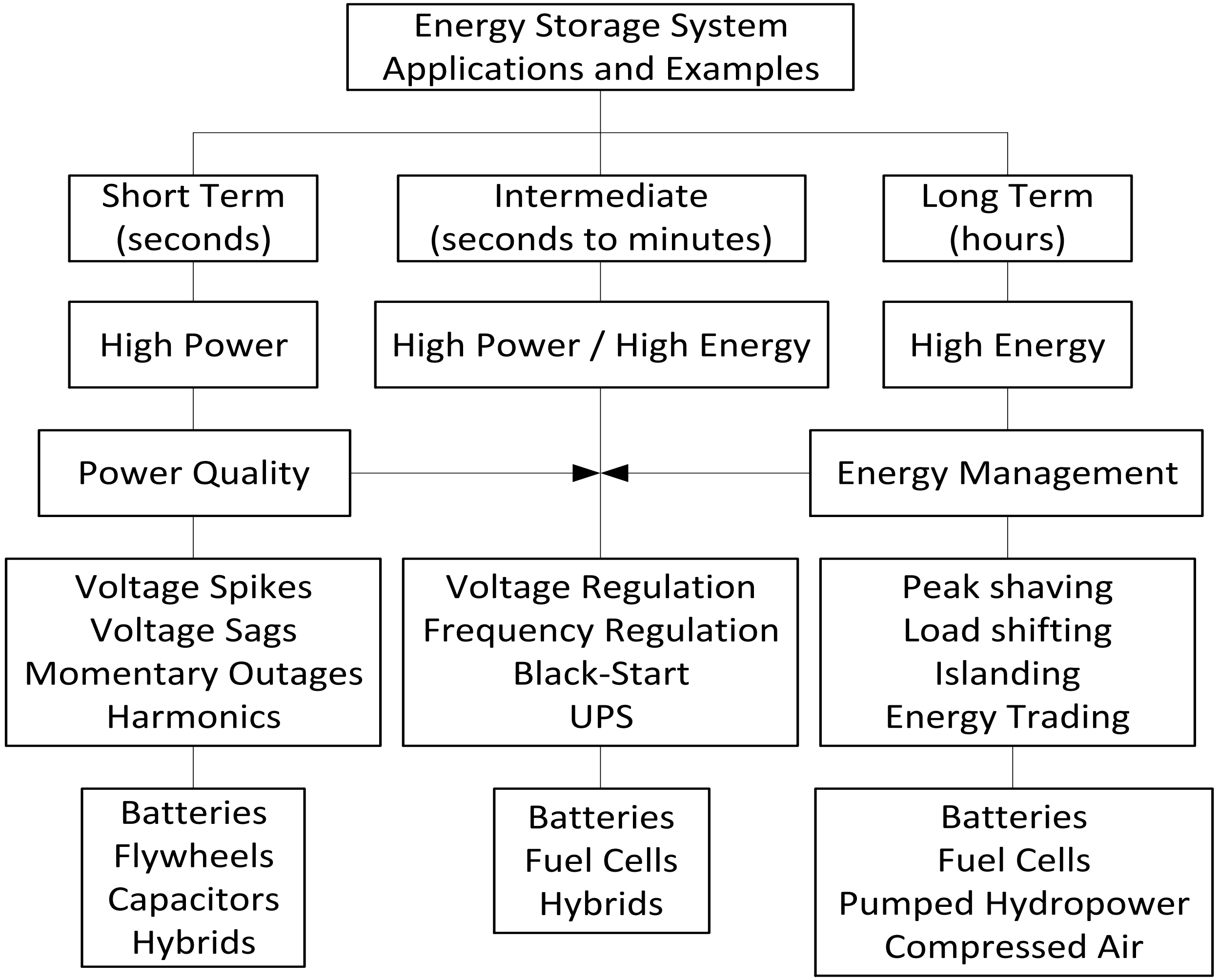
- ***Energy Storage Systems are distributed along the entire network.***
- Energy Storage could be used to improve:
  - The grid’s stability and reliability.
  - Energy Management
    - *Peak Shaving*
    - *Load Shifting*
  - Optimization and Planning
    - *Economic Dispatch*
    - *Minimum Production Cost*
  - etc



SMART GRID – A real-time dynamic network of electrical demand, supply and control (Photo Credit: David Blaza and utilityproducts.com [144] using Written License Consent)

Energy Storage Systems

Applications and Examples



Energy Storage System Applications and Examples

Short Term (seconds)

Intermediate (seconds to minutes)

Long Term (hours)

High Power

High Power / High Energy

High Energy

Power Quality

Energy Management

Voltage Spikes
Voltage Sags
Momentary Outages
Harmonics

Voltage Regulation
Frequency Regulation
Black-Start
UPS

Peak shaving
Load shifting
Islanding
Energy Trading

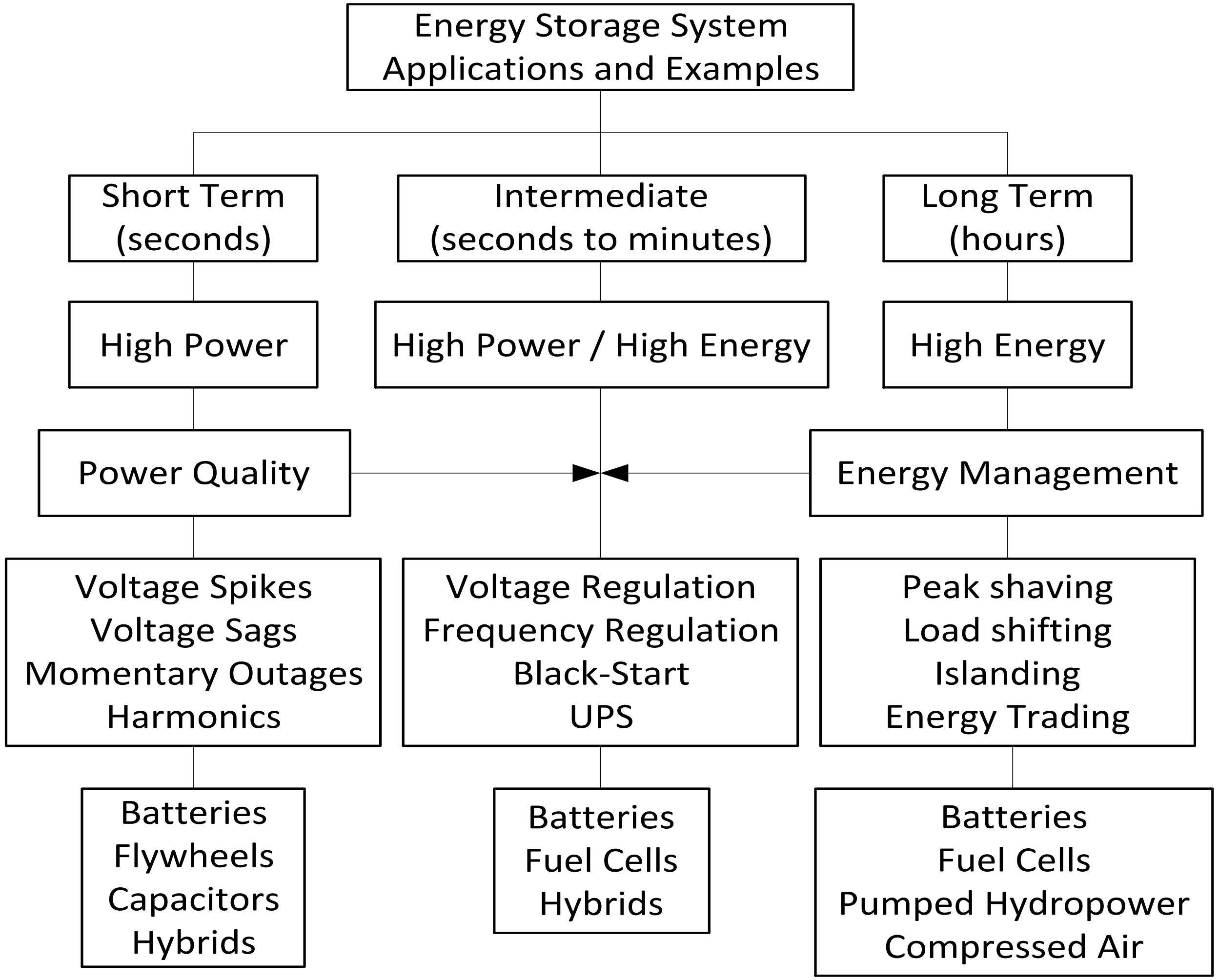
Batteries
Flywheels
Capacitors
Hybrids

Batteries
Fuel Cells
Hybrids

Batteries
Fuel Cells
Pumped Hydropower
Compressed Air

Energy Storage Systems

Applications and Examples


Energy Storage System Applications and Examples

Short Term (seconds)
High Power
Power Quality
Voltage Spikes
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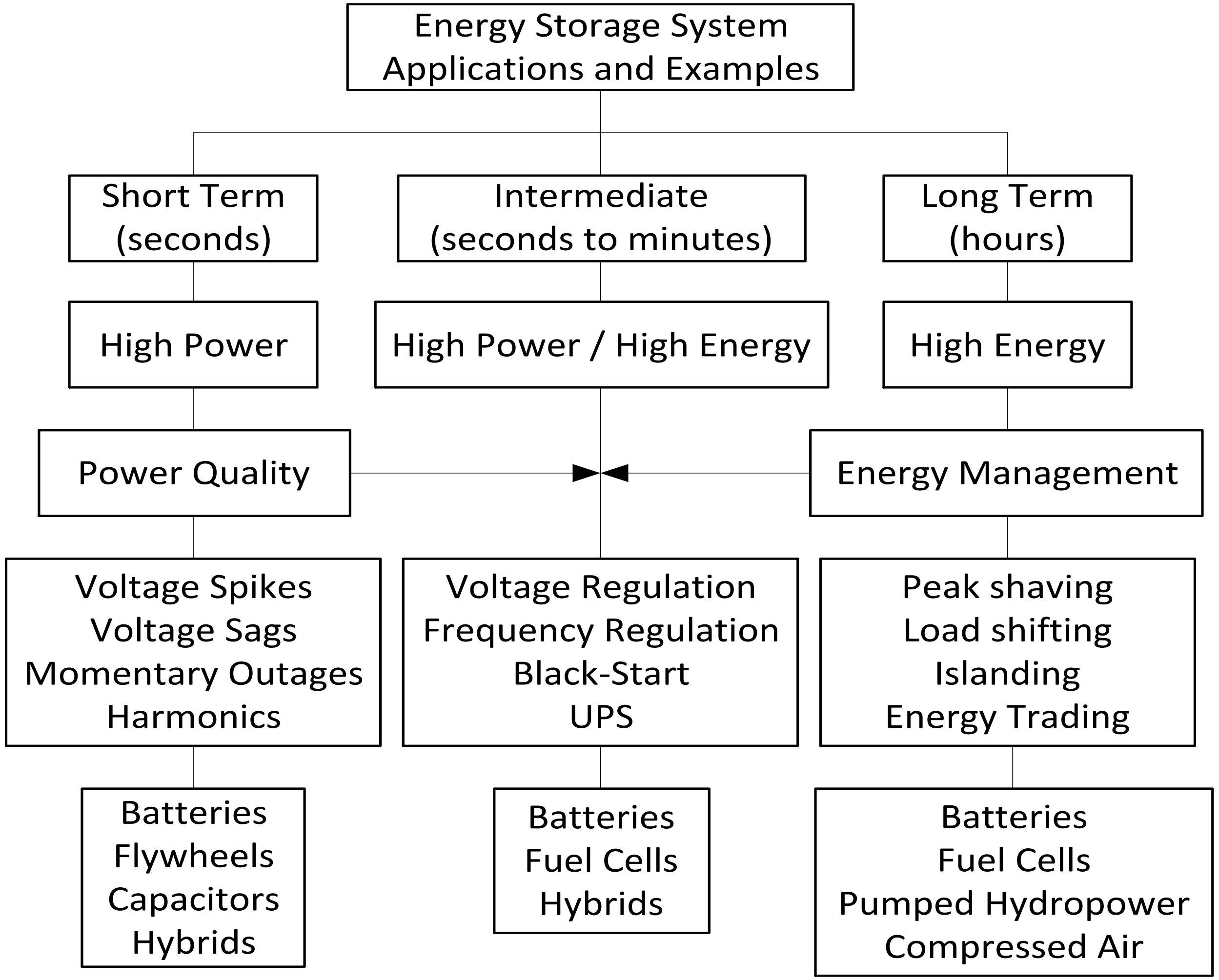
Long Term (hours)
High Energy
Energy Management
Peak shaving
Load shifting
Islanding
Energy Trading
Batteries
Fuel Cells
Pumped Hydropower
Compressed Air

○ Energy Storage Systems
- Under 3 Categories
  - *Short Term*
  - *Intermediate*
  - *Long Term*

Energy Storage Systems

Applications and Examples



Energy Storage System Applications and Examples

Short Term (seconds)
High Power
Power Quality
Voltage Spikes
Voltage Sags
Momentary Outages
Harmonics
Batteries
Flywheels
Capacitors
Hybrids

Intermediate (seconds to minutes)
High Power / High Energy
Voltage Regulation
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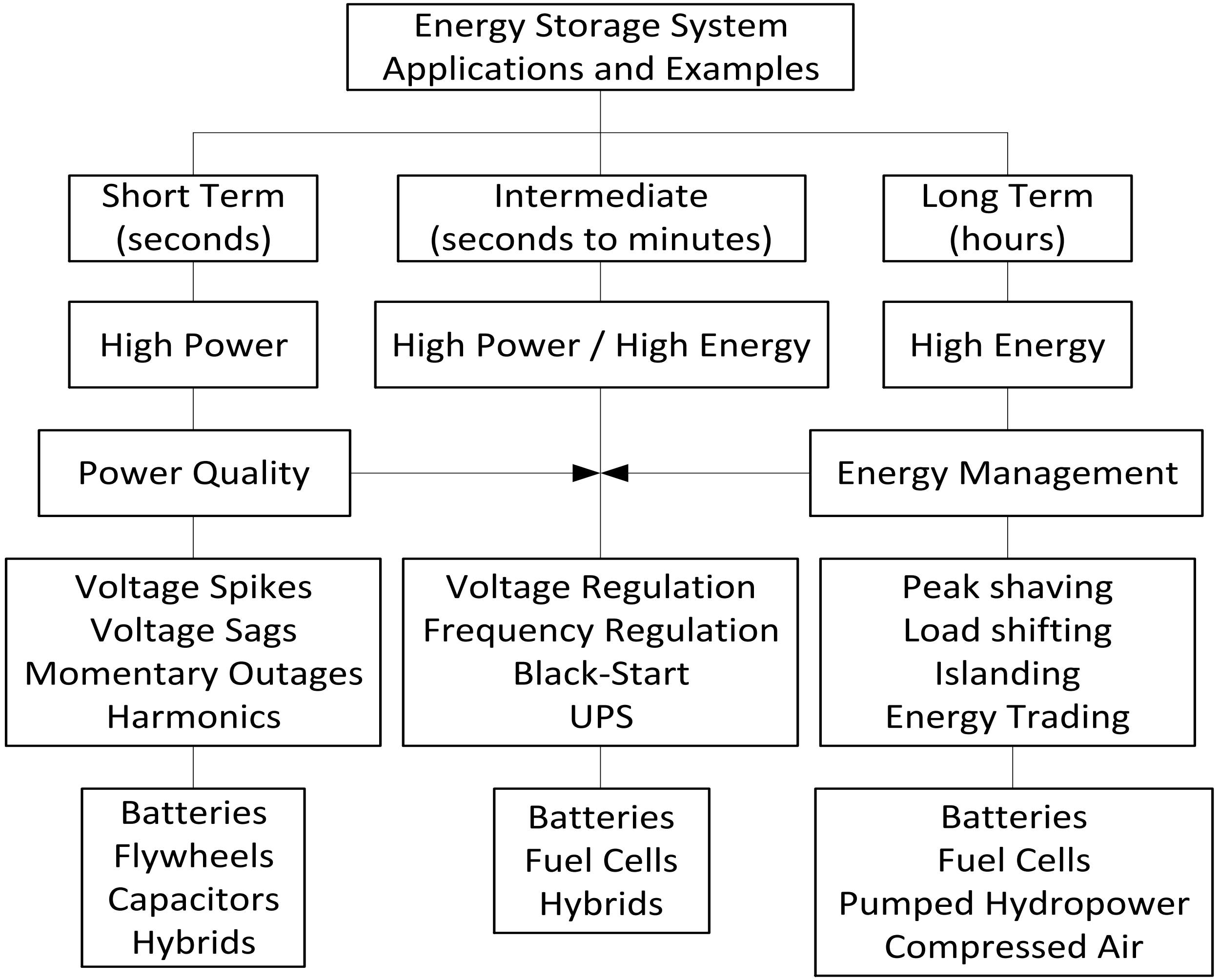
Long Term (hours)
High Energy
Energy Management
Peak shaving
Load shifting
Islanding
Energy Trading
Batteries
Fuel Cells
Pumped Hydropower
Compressed Air

- Energy Storage Systems
  - Under 3 Categories
    - *Short Term*
      - Duration in seconds
    - *Intermediate*
      - Duration between seconds to minutes
    - *Long Term*
      - Duration in hours

Energy Storage Systems

Applications and Examples



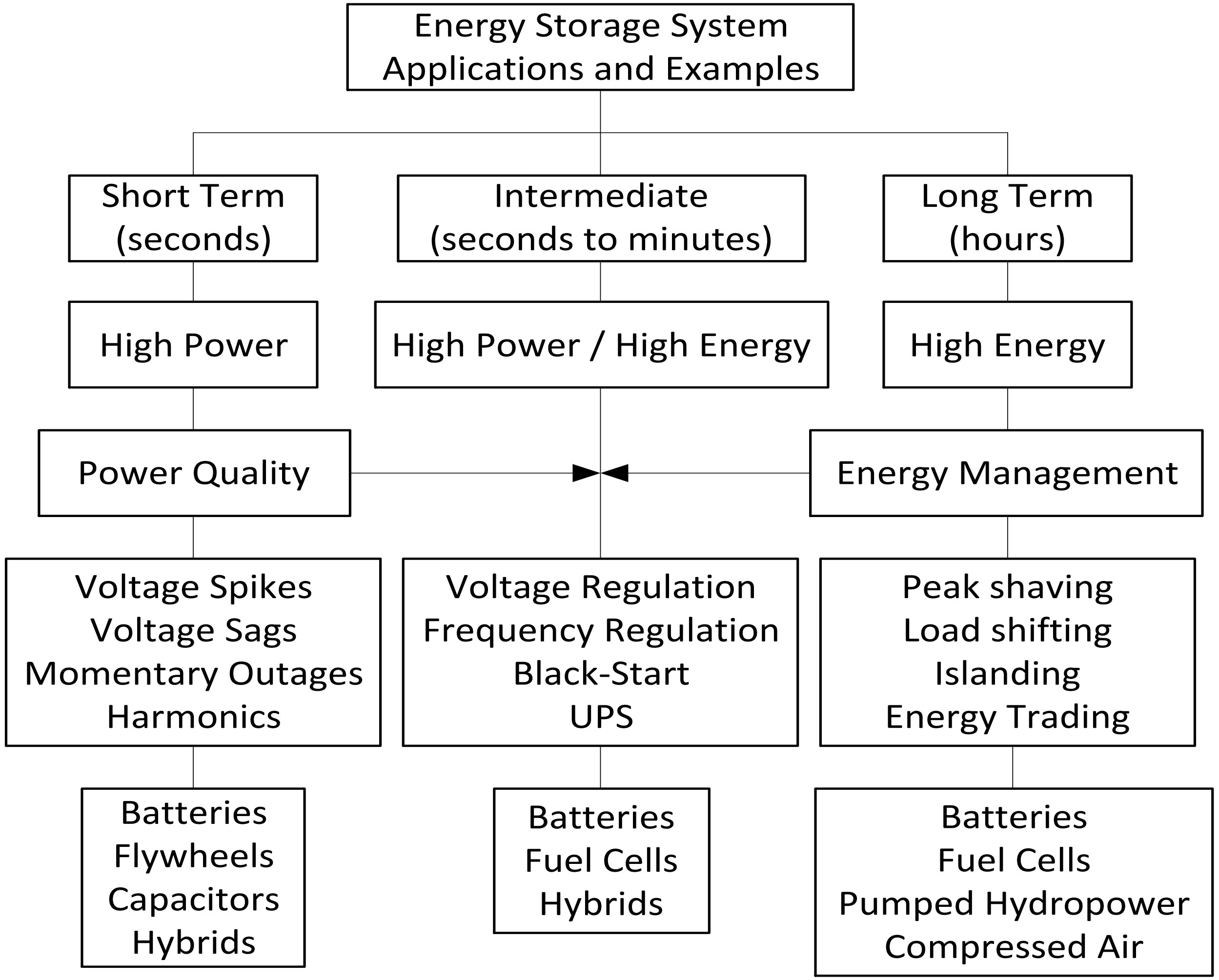
Energy Storage System Applications and Examples

Short Term (seconds)	Intermediate (seconds to minutes)	Long Term (hours)
High Power	High Power / High Energy	High Energy
Power Quality		Energy Management
Voltage Spikes Voltage Sags Momentary Outages Harmonics	Voltage Regulation Frequency Regulation Black-Start UPS	Peak shaving Load shifting Islanding Energy Trading
Batteries Flywheels Capacitors Hybrids	Batteries Fuel Cells Hybrids	Batteries Fuel Cells Pumped Hydropower Compressed Air

- Energy Storage Systems
  - Under 3 Categories
    - *Short Term*
      - Duration in seconds
      - Require High Power
    - *Intermediate*
      - Duration between seconds to minutes
      - Require a combination of high power and high energy
    - *Long Term*
      - Duration in hours
      - Require High Energy

Energy Storage Systems

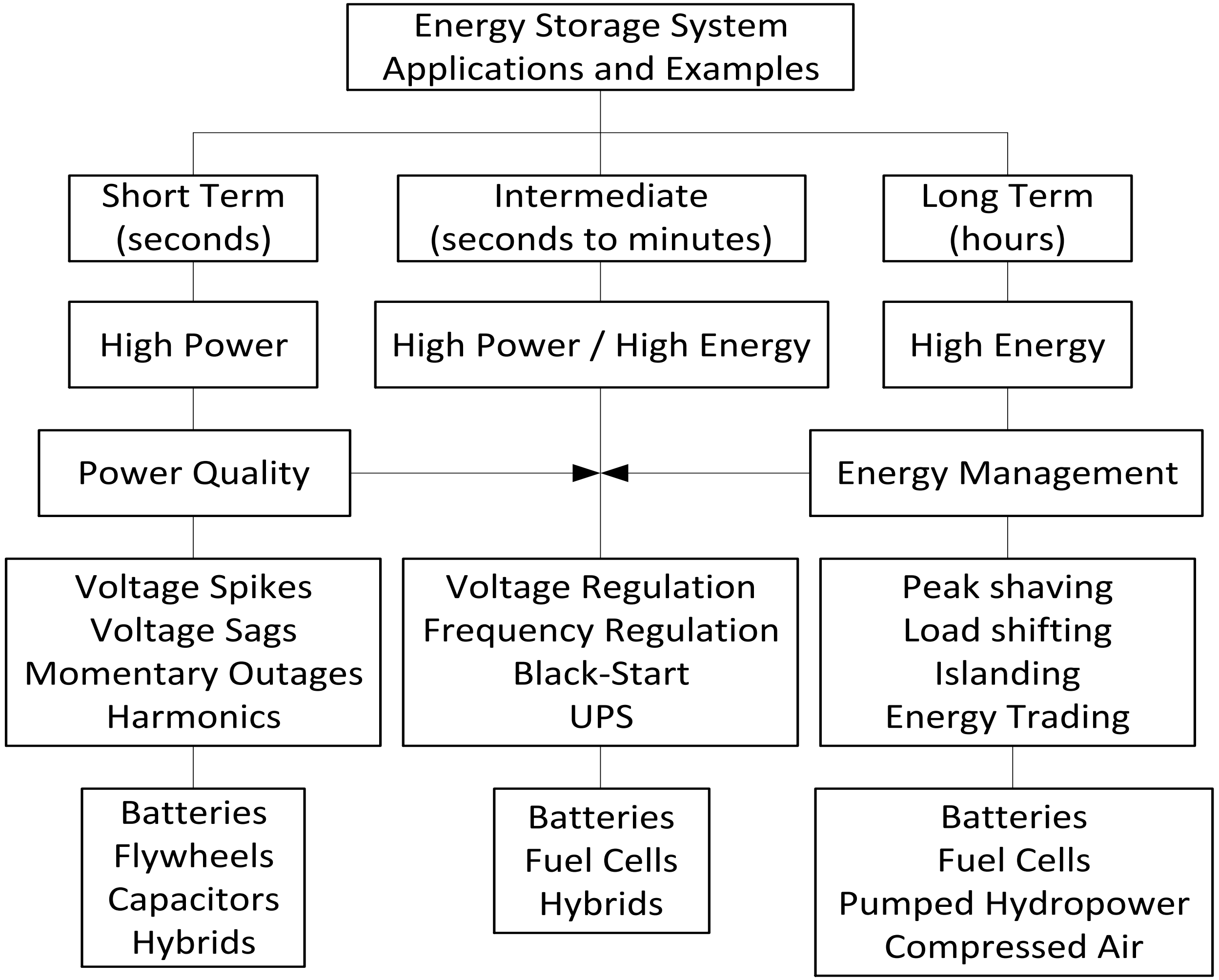
Applications and Examples



○ Energy Storage Systems
- Applications
  - *Short Term*
    - Power Quality
      - Voltage spikes, voltage sags, momentary outages and harmonics
  - *Intermediate*
    - Regulation (voltage and frequency), Uninterruptable power supplies and Black-Start
    - Black-start is the process of recovering from a total or partial outage
  - *Long Term*
    - Energy Management
      - Peak shaving, load shifting, islanding, energy trading, etc

Energy Storage Systems

Applications and Examples



Energy Storage System Applications and Examples

Short Term (seconds)

Intermediate (seconds to minutes)

Long Term (hours)

High Power

High Power / High Energy

High Energy

Power Quality

Energy Management

Voltage Spikes
Voltage Sags
Momentary Outages
Harmonics

Voltage Regulation
Frequency Regulation
Black-Start
UPS

Peak shaving
Load shifting
Islanding
Energy Trading

Batteries
Flywheels
Capacitors
Hybrids

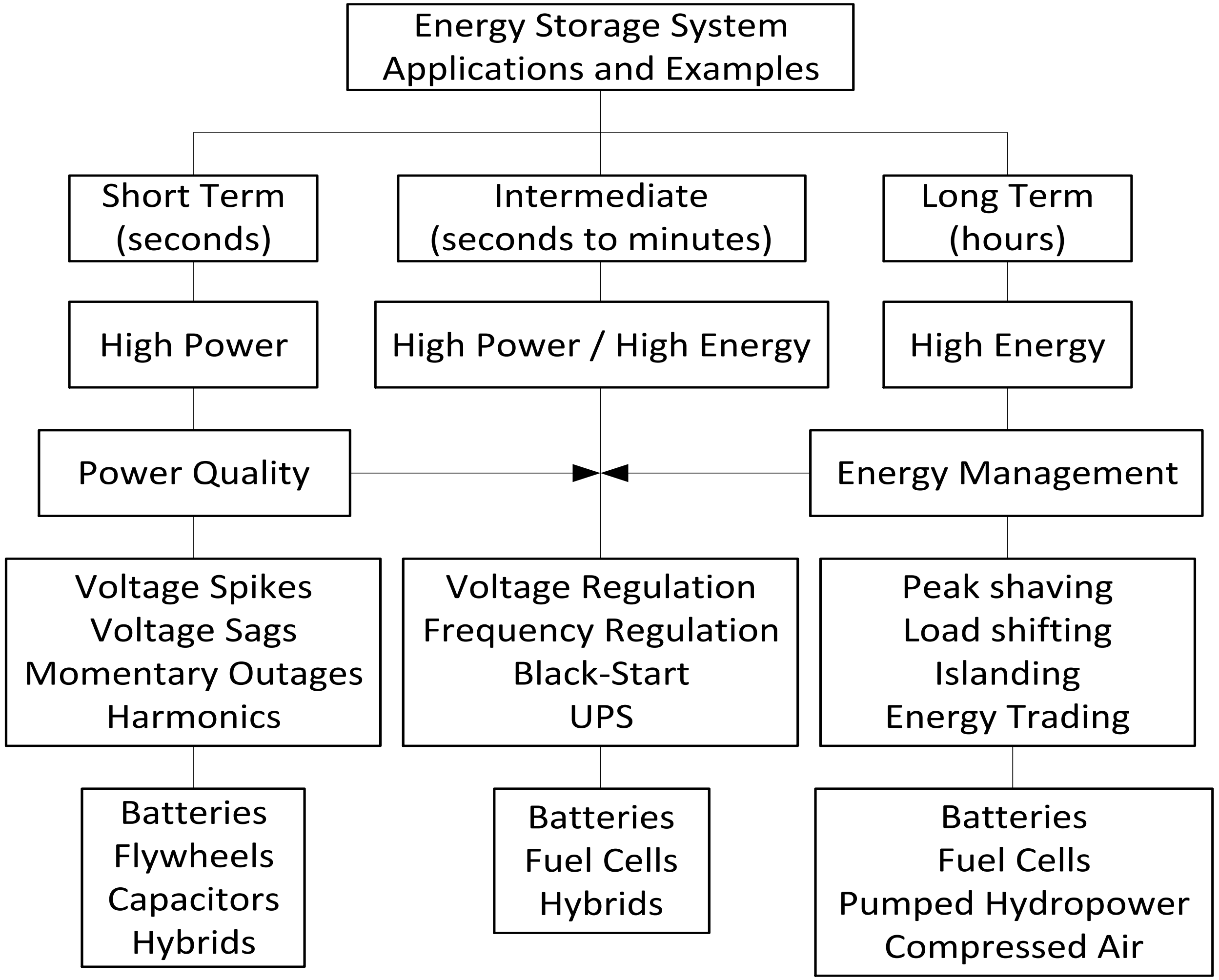
Batteries
Fuel Cells
Hybrids

Batteries
Fuel Cells
Pumped Hydropower
Compressed Air

- Energy Storage Systems
  - Commercially Available Technologies
    - *Short Term*
      - Batteries, Flywheels, Capacitors and Hybrids (Battery & Capacitor)
    - *Intermediate*
      - Batteries, Fuel Cells, Hybrids
    - *Long Term*
      - Batteries, Fuel Cells, Pumped Hydro and Compressed Air

Energy Storage Systems

Applications and Examples



Energy Storage System Applications and Examples

Short Term (seconds)

High Power

Power Quality

Voltage Spikes
Voltage Sags
Momentary Outages
Harmonics

Batteries
Flywheels
Capacitors
Hybrids

Intermediate (seconds to minutes)

High Power / High Energy

Voltage Regulation
Frequency Regulation
Black-Start
UPS

Batteries
Fuel Cells
Hybrids

Long Term (hours)

High Energy

Energy Management

Peak shaving
Load shifting
Islanding
Energy Trading

Batteries
Fuel Cells
Pumped Hydropower
Compressed Air

- Energy Storage Systems
  - Commercially Available Technologies
    - *Short Term*
      - Batteries, Flywheels, Capacitors and Hybrids (Battery & Capacitor)
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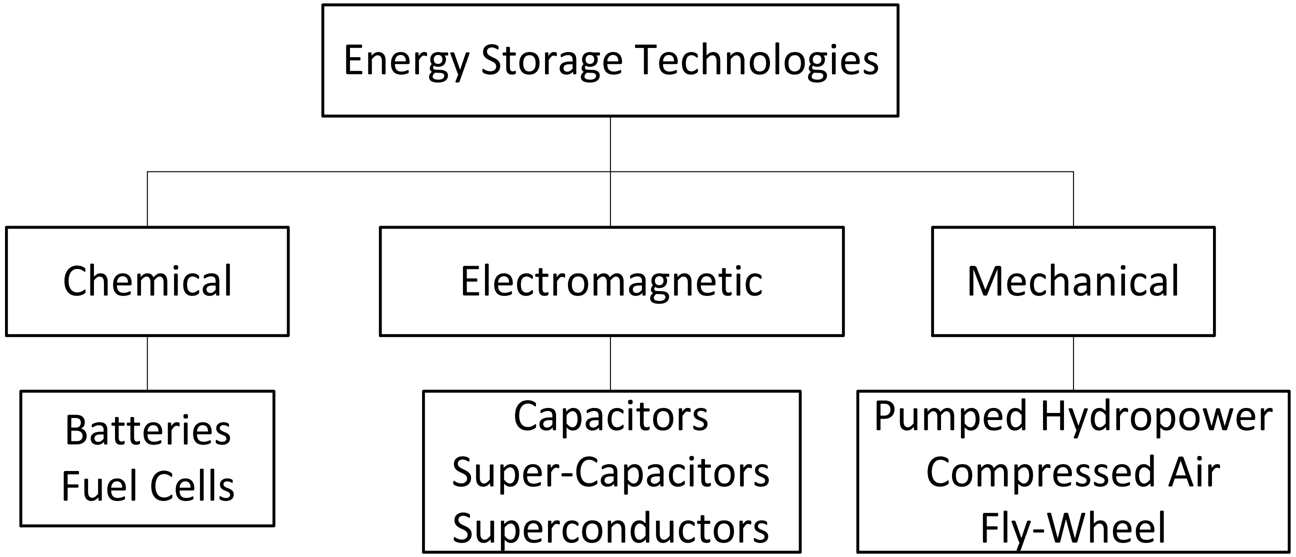
    - *Long Term*
      - Batteries, Fuel Cells, Pumped Hydro and Compressed Air
    - *Notice how batteries can be used for all applications*

Energy Storage Systems

Classification



Energy Storage Technologies

Chemical

- Batteries
- Fuel Cells

Electromagnetic

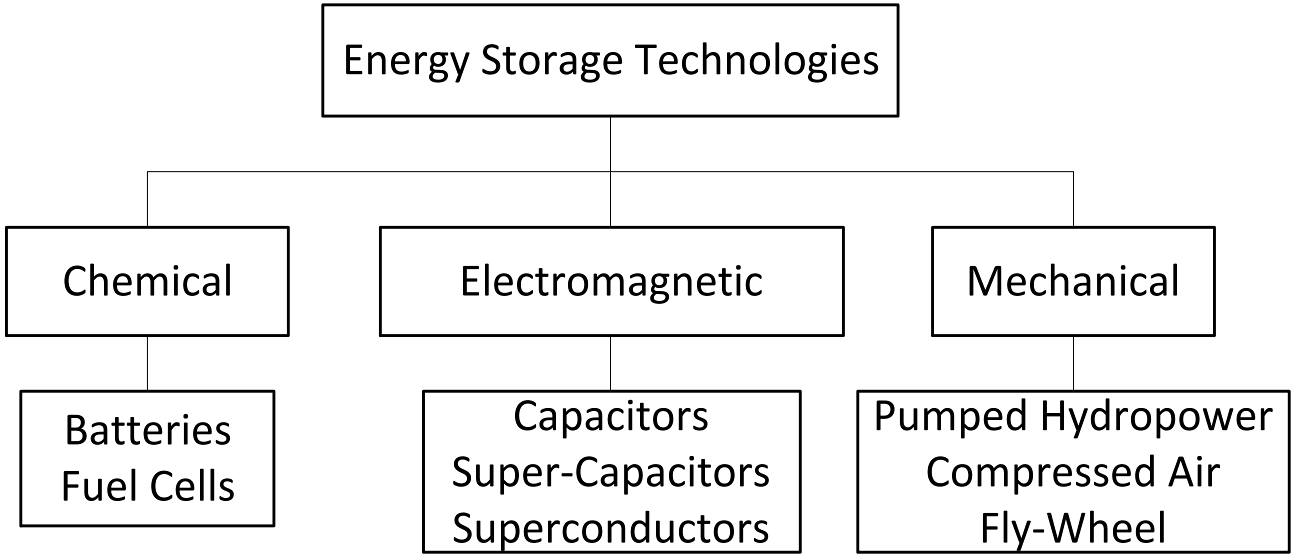
- Capacitors
- Super-Capacitors
- Superconductors

Mechanical

- Pumped Hydropower
- Compressed Air
- Fly-Wheel

Energy Storage Systems

Classification


Energy Storage Technologies

Chemical

Electromagnetic

Mechanical

Batteries
Fuel Cells

Capacitors
Super-Capacitors
Superconductors

Pumped Hydropower
Compressed Air
Fly-Wheel

- Energy Storage Systems
  - 3 Classes
    - *Chemical*
    - *Electromagnetic*
    - *Mechanical*

Energy Storage Systems

Important Terminology

- Round-Trip Efficiency
  - Also known as the AC/AC efficiency
  - Round trip efficiency takes into consideration the amount of energy stored in the storage system and amount of delivered or retrieved energy

Energy Storage Systems

Important Terminology

○ Round-Trip Efficiency

- Also known as the AC/AC efficiency
- Round trip efficiency takes into consideration the amount of energy stored in the storage system and amount of delivered or retrieved energy
- Some Indicative Values

Energy Storage Technology	**Round-Trip Efficiency (%)**
Pumped Hydropower	65-80
Flywheels	80-90
Batteries	75-90
Compressed Air (CAES)	65-75

Energy Storage Systems

Important Terminology

- Round-Trip Efficiency
  - Also known as the AC/AC efficiency
  - Round trip efficiency takes into consideration the amount of energy stored in the storage system and amount of delivered or retrieved energy
  - Some Indicative Values

Energy Storage Technology	Round-Trip Efficiency (%)
Pumped Hydropower	65-80
Flywheels	80-90
Batteries	75-90
Compressed Air (CAES)	65-75

Battery Technology

Definition

- Batteries are chemical devices.
- Batteries are devices that stores electrical charge.
- Batteries are composed of two electrodes and an electrolyte.
- By oxidation and reduction of the electrodes, chemical energy is converted to electrical energy.

Battery Technology

Definition

- ○ Secondary Batteries
  - Rechargeable
- ○ Primary Batteries
  - Non- rechargeable

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
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Batteries

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- Energy Density
  - Total Energy / Total Weight
  - Units: Wh/kg

Batteries

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- Energy Density
  - Total Energy / Total Weight
  - Units: Wh/kg
  - Also known as
    - *Gravimetric Energy Density*

Batteries

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○ Energy Density
- Total Energy / Total Weight
- Units: Wh/kg
- Also known as
  - *Gravimetric Energy Density*
- For applications with volume restrictions
  - *i.e. Unmanned Systems*
  - *Volumetric Energy Density (Wh/m^3)*

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- Energy Density (Wh/kg)
- Is the product of
  - Battery Capacity (Ah)
  - Battery Voltage (V)

Batteries

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- Energy Density (Wh/kg)
- Is the product of
  - Battery Capacity (Ah)
  - Battery Voltage (V)
- Battery Capacity
  - Discharge Current (A)
  - Discharge Time (h)

Batteries

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- Internal Resistance
  - Units: mΩ

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  - Units: mΩ
  - Inversely Proportional to the battery’s efficiency (η)

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- ○ Internal Resistance
  - Units: mΩ
  - Inversely Proportional to the battery’s efficiency (η)
    - As R ↑ then η ↓
    - As R ↓ then η ↑

Batteries

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- Life Cycle
  - The number of times a battery is charged and discharged

Batteries

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- Life Cycle
  - The number of times a battery is charged and discharged
- Depth of Discharge (DoD)

Batteries

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- Life Cycle
  - The number of times a battery is charged and discharged
- Depth of Discharge (DoD)
  - 100% DoD → Empty
  - 0% DoD → Full

Batteries

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- Life Cycle
  - The number of times a battery is charged and discharged
- Depth of Discharge (DoD)
  - 100% DoD → Empty
  - 0% DoD → Full
- Safety Limits
  - 80-95% DoD
  - According to manufacturer, technology, etc

Batteries

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- Safety limits ensure that the chemical reaction is reversible

- Life Cycle
  - The number of times a battery is charged and discharged
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- Cell Voltage
  - Open Circuit Voltage

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- Cell Voltage
  - Open Circuit Voltage
    - No load connected
    - Current is 0A

Batteries

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In Commercial Use Since	1950	1990	1970	1991	1992

- Cell Voltage
  - Open Circuit Voltage
    - No load connected
    - Current is 0A
  - Cells are connected in series to achieve the desired operating voltage

Batteries

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Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (ºC)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- When cell-voltage drops below a safety level then reaction becomes irreversible
  - According to manufacturer, technology, etc

- Cell Voltage
  - Open Circuit Voltage
    - No load connected
    - Current is 0A
  - Cells are connected in series to achieve the desired operating voltage

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Load Current
  - Current is measured in Amperes

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Load Current
  - Current is measured in Amperes
- Another Important Term
  - *Discharge Rate* (C-Rate)
  - $C = I \times Discharge\ Time$

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Load Current
  - Current is measured in Amperes
- Another Important Term
  - *Discharge Rate* (C-Rate)
  - *C = I x Discharge Time*
  - 1C → *discharge t=1hr*
  - 0.2C → *discharge t=5hr*

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (ºC)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Load Current
  - Current is measured in Amperes
- Another Important Term
  - *Discharge Rate* (C-Rate)
  - *C = I x Discharge Time*
  - A battery rated at 70Ah discharged at 1C

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Load Current
  - Current is measured in Amperes
- Another Important Term
  - *Discharge Rate* (C-Rate)
  - *C = I x Discharge Time*
  - A battery rated at 70Ah discharged at 1C
    - I = 70Ah / 1C = 70Ah/1h = 70A

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- When battery maximum current is exceeded then the battery could suffer catastrophic failure (catch fire)
  - According to manufacturer, technology, etc

- Load Current
  - Current is measured in Amperes
- Another Important Term
  - *Discharge Rate* (C-Rate)
  - *C = I x Discharge Time*
  - A battery rated at 70Ah discharged at 1C
    - I = 70Ah / 1C = 70Ah/1h = 70A

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
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Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Operating Temperature Range
  - Normal Operation

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Operating Temperature Range
  - Normal Operation
- At Low Temperatures
  - Loss of capacity
  - Low efficiency

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
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Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Operating Temperature Range
  - Normal Operation
- At Low Temperatures
  - Loss of capacity
  - Low efficiency
- At High Temperatures
  - May suffer catastrophic failure

Batteries

Important Terminology

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Year Since in Commercial Use
  - *Technology*
    - Maturity
    - Understanding

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)
- Most Mature Technology

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)
- Most Mature Technology
- High Power Applications

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
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Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)
- Most Mature Technology
- High Power Applications
- Low Energy Density

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
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Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)
- Most Mature Technology
- High Power Applications
- Low Energy Density
- Low Resistance / High Efficiency

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
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Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Cadmium (NiCad)
- Most Mature Technology
- High Power Applications
- Low Energy Density
- Low Resistance / High Efficiency
- High Cycle Life

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Metal Hydride (NiMH)

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Metal Hydride (NiMH)
- Relatively New Technology

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Metal Hydride (NiMH)
- Relatively New Technology
- Compared to NiCad
  - Higher Energy Density

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Nickel Metal Hydride (NiMH)
- Relatively New Technology
- Compared to NiCad
  - Higher Energy Density
  - Lower Cycle Life
  - Lower Power Density
  - More Expensive

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Sealed Lead Acid (SLA)
- Mature Technology

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Sealed Lead Acid (SLA)
- Mature Technology
- Cheapest Technology

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Sealed Lead Acid (SLA)
- Mature Technology
- Cheapest Technology
- Lowest Energy and Power Densities
- Lowest Cycle Life

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Sealed Lead Acid (SLA)
- Mature Technology
- Very Cheap Technology
- Lowest Energy and Power Densities
- Lowest Cycle Life
- Highest Efficiency

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (^{o}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Lithium Ion (Li-Ion)
- New Technology

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
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Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Lithium Ion (Li-Ion)
- New Technology
- Highest Energy Densities
- High Power Density
- Highest Cell Voltage
- High Cycle Life

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
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Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Lithium Ion (Li-Ion)
- New Technology
- Highest Energy Densities
- High Power Density
- Highest Cell Voltage
- High Cycle Life
- Most Expensive

Batteries

Various Chemistries

	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	\$50	\$70	\$25	\$100	\$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Reusable Alkaline
- Cheapest Technology
- Highest Cycle Life

Batteries

Various Chemistries

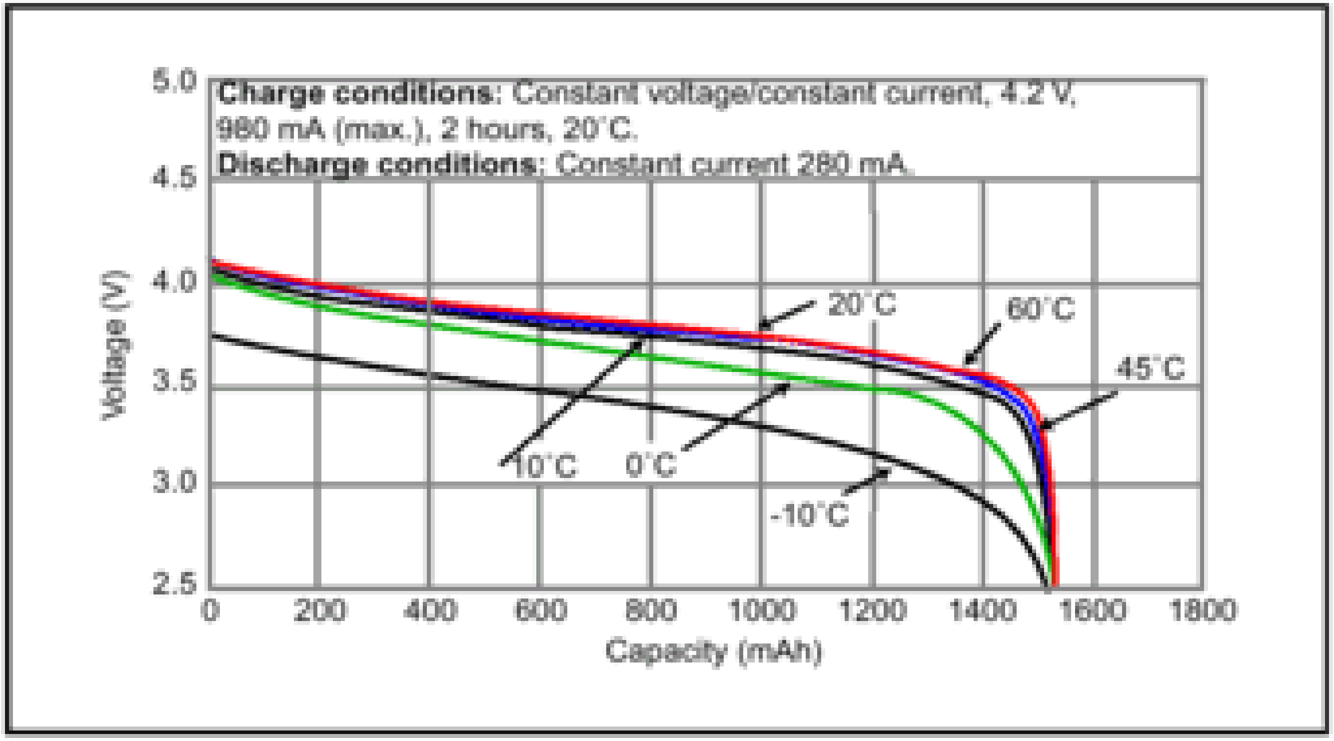
	NiCad	NiMH	SLA	Li-Ion	Reusable Alkaline
Energy Density (Wh/Kg)	40-60	60-80	30	165	80 (initial)
Internal Resistance (mΩ)	100-300	200-800	<100	300-500	200-2000
Cycle Life	1500	500	200-300	500-1000	10000
Cell Voltage	1.2	1.2	2	3.6	1.5
Load Current	>2C	0.5-1C	0.2C	2C	0.2C
Operating Temperature (°C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	0 to 65
Cost	$50	$70	$25	$100	$5
In Commercial Use Since	1950	1990	1970	1991	1992

- Reusable Alkaline
- Cheapest Technology
- Highest Cycle Life
- Very Low Efficiency
- Low Power Applications

Batteries

Capacity Vs Temperature

- Loss of Capacity at Lower Temperatures

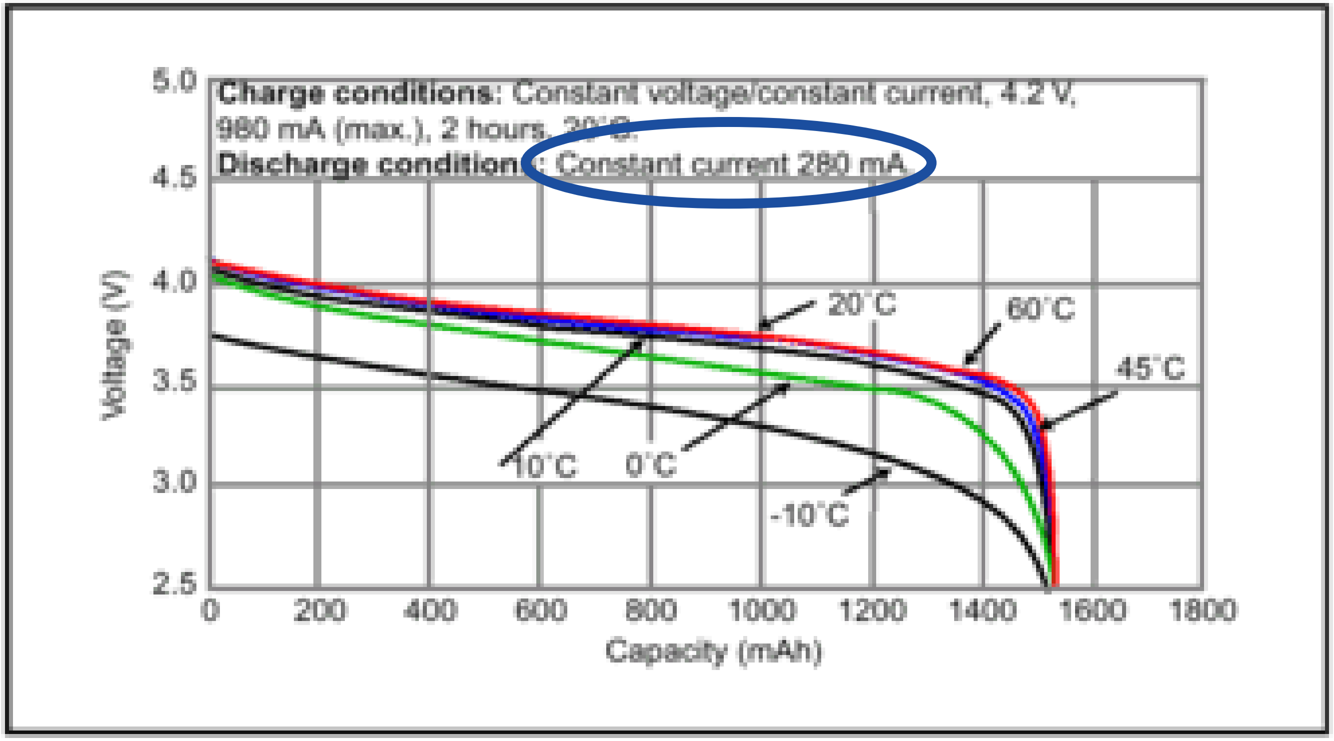


Discharge Versus Temperature Characteristics of a Typical Lithium Ion 18650 Cell from [176].

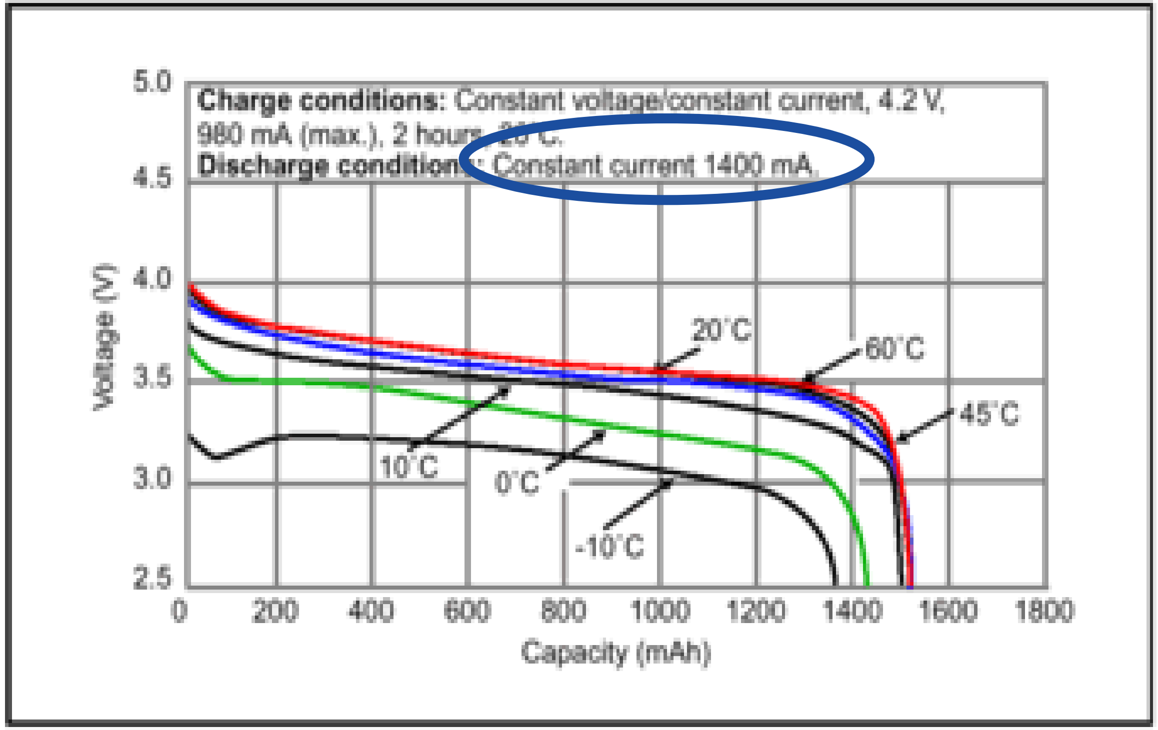
Batteries

Capacity Vs Temperature

- Loss of Capacity at Lower Temperatures
- Loss of Capacity at Higher Discharge Currents



Discharge Versus Temperature Characteristics of a Typical Lithium Ion 18650 Cell from [176].

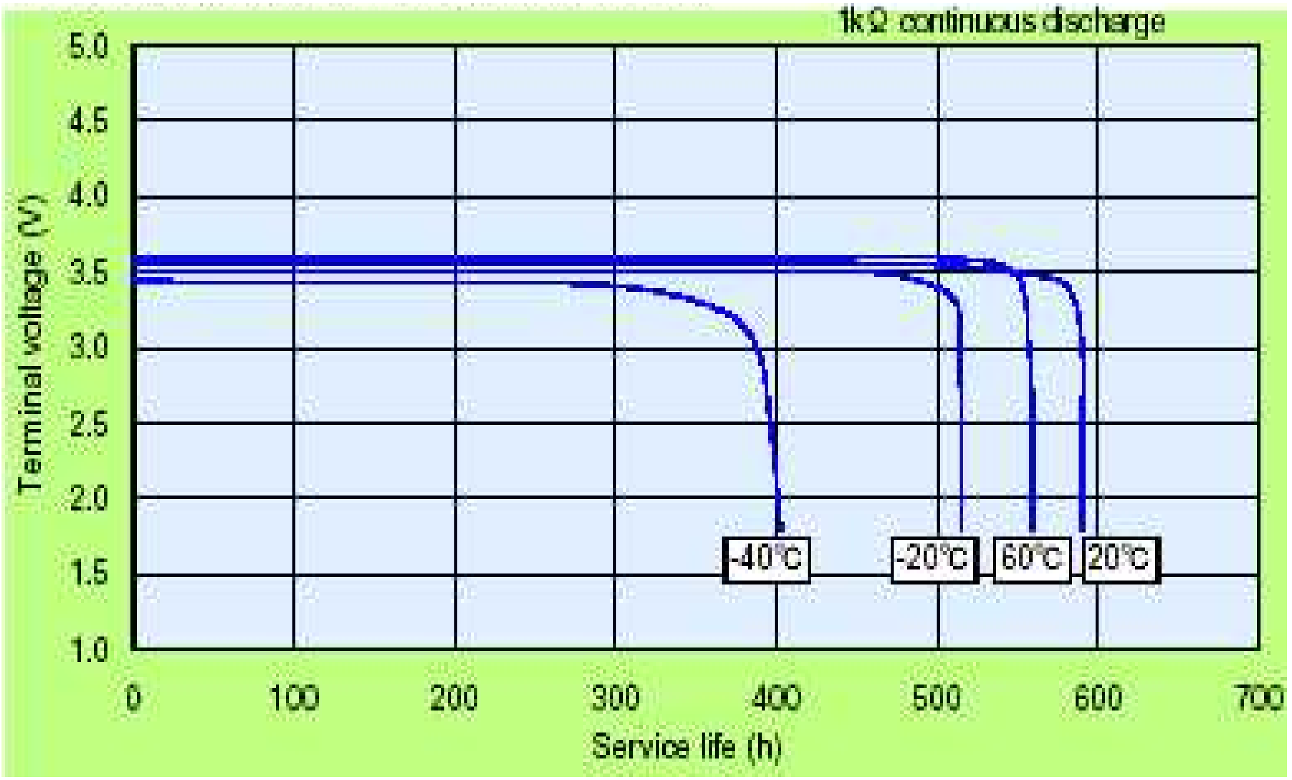


High Rate Discharge Characteristics of Typical Lithium Ion 18650 Cell from [176].

Batteries

Service Life Vs Temperature

- Loss of Service Life at Lower Temperatures



Discharge Versus Temperature Characteristics for Toshiba (ER6VP) Thionyl Chloride Lithium Battery With 3.6V Nominal Voltage and 2000mAh Capacity and 16gr. Weight from [170].

Batteries

Peukert's Equation

- Battery capacity is depended on the discharge current, the latter usually expressed as a fraction of the numerical value of the capacity.
- At higher discharge currents (high discharge rate) the battery efficiency decreases and as a result less energy is delivered.
- The first mathematical model that captures this effect also known as Peukert's equation is given by:

$$\boldsymbol{C_p = I^p t}$$

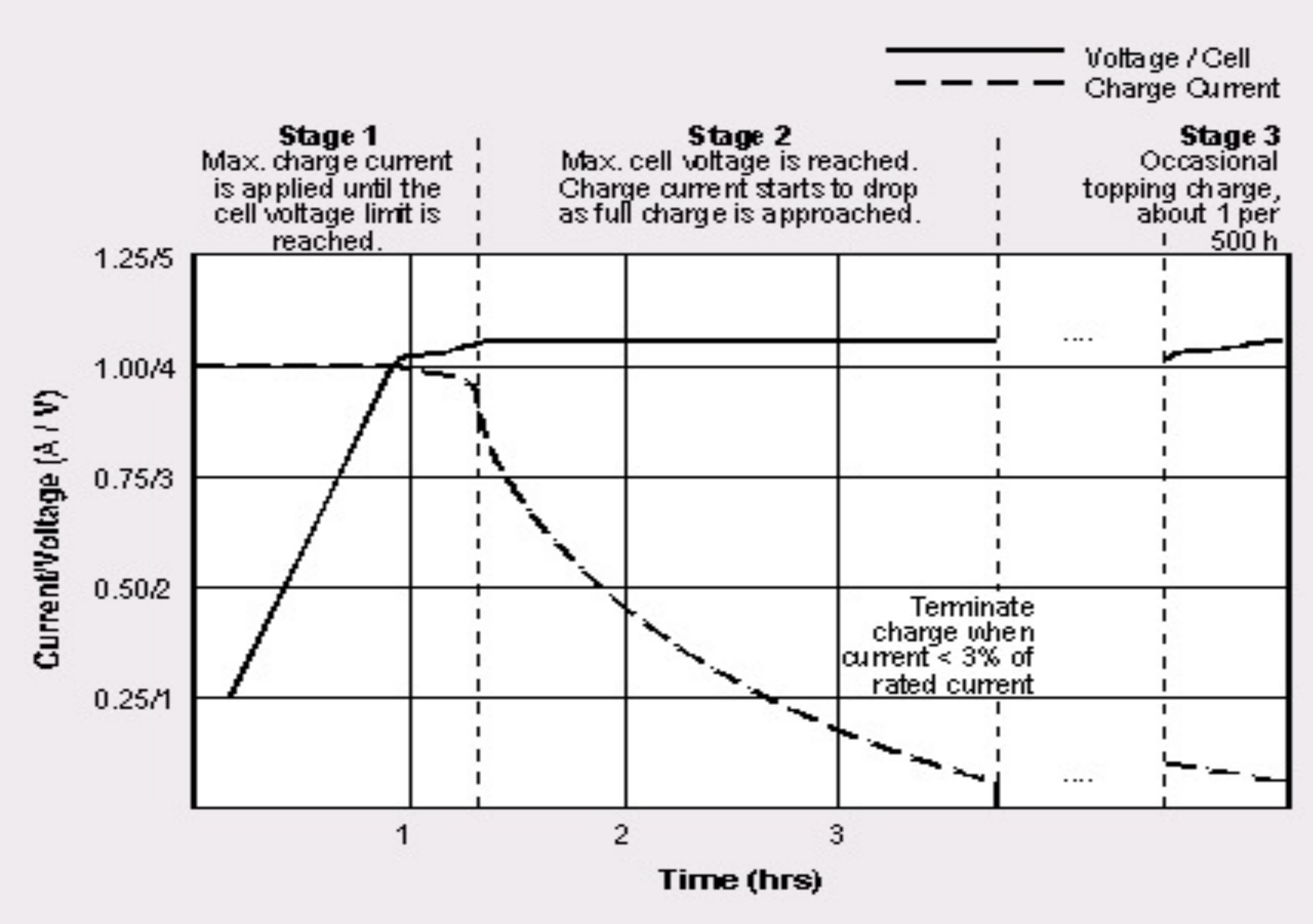
- where C_p is the Peukert's battery capacity, I the discharge current, t the time and p Peukert's exponent usually between 1.1 and 1.4 dependent on the battery [187], [188].

Batteries

Charging Process

- Maximum current is applied until the cell voltage is reached.
- The current is slowly decreased.
- Trickle charge is applied.

- **Note:**
- Lithium
  - Cell voltage 3.7v / cell
  - Charged to 4.2v / cell
- SLA
  - Cell voltage 2v / cell
  - Charged to 2.4v / cell



Three Stage Charging Process of Lithium Ion Batteries from [164], [168].

Fuel Cells

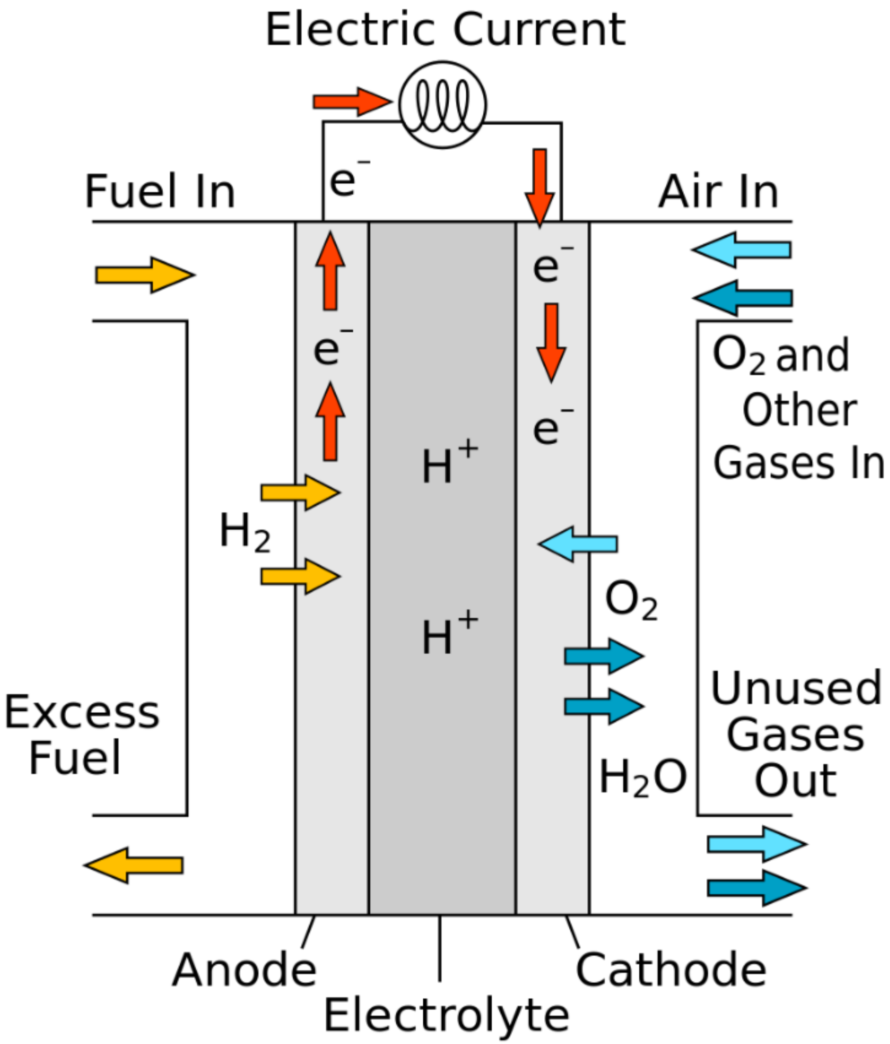
Comparison

- Chemical devices like batteries
- Advantage
  - Fuel-cell’s refueling is very fast (minutes) whereas battery’s recharging is in the range of hours.
- Disadvantage
  - Fuel-cell’s cell voltage is in the range of 0.6 to 0.875v whereas batteries are in the range of 1.2 to 3.7v.
    - *More connected cells increase the possibility of a failure as an open-circuit.*

Fuel Cells

Block Diagram

- ○ Parts
  - Anode
  - Electrolyte
  - Cathode
- ○ Fuel
  - Hydrogen enters on the Anode side
  - Oxygen (air) enters on the Cathode side
- ○ By-products
  - Electricity
  - Heat
  - Water



Fuel Cells

Chemical Reactions

- The basic hydrogen fuel cell operation is given by two reactions that occur concurrently. At the anode of an acid electrolyte, hydrogen gas ionizes releasing two electrons, two mobile protons (H^+) and energy.

$$2H_2 \rightarrow 4H^+ + 4e^-$$

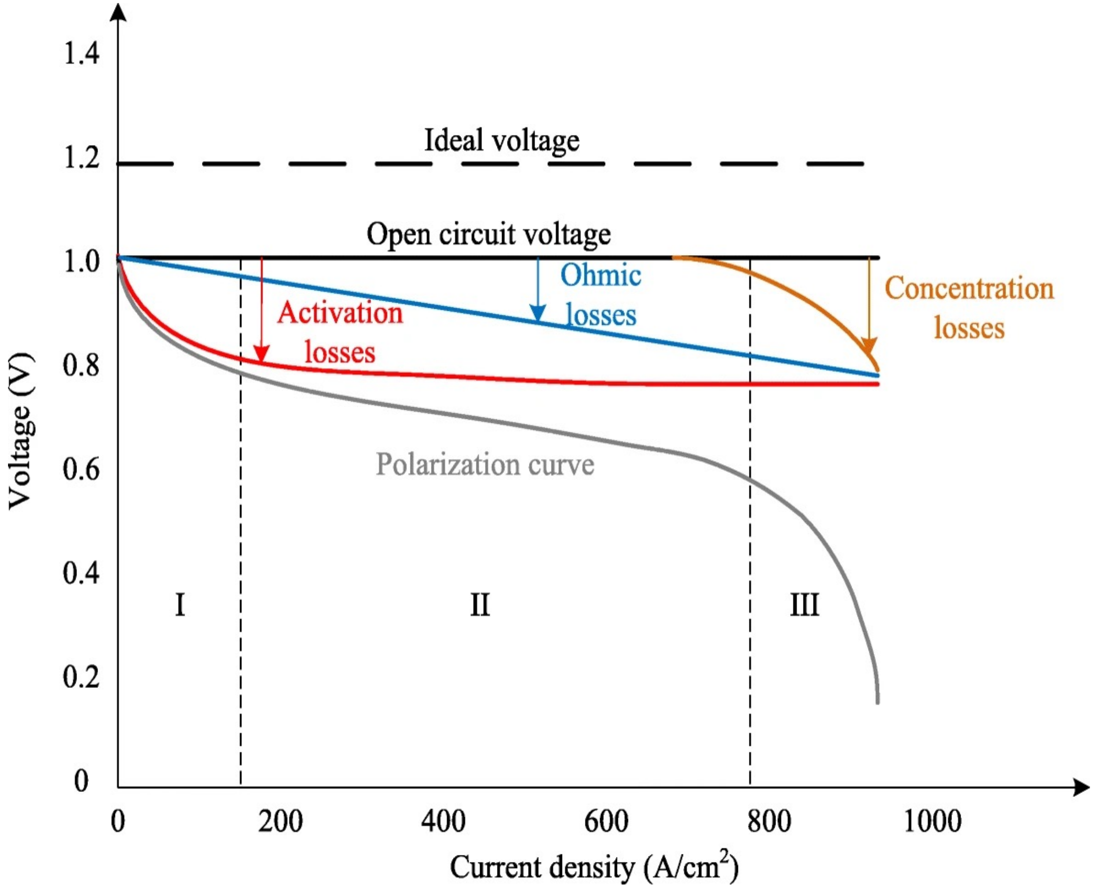
- The mobile protons will travel through the acid electrolyte to the cathode, whereas the electrons cannot go through and are forced to travel through an external connection provided by the load. At the cathode, oxygen reacts with the proton taken from the electrolyte and electrons arriving externally, to form water.

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$$

Fuel Cells

Performance Metrics

- The performance of fuel cells is affected by pressure and temperature
- At low temperature and air pressure the theoretical or "No loss" cell voltage is 1.2V.
- However, the actual open circuit voltage is approximately 1V.
- These differences are due to four major "irreversibilities"
  - Activation losses
  - Fuel crossover and internal currents
  - Ohmic losses
  - Mass transport or concentration losses



I-V Characteristics and Losses of PEMFC (Credit: Zhongliang Li, Open Access Creative Commons Attribution 4.0 International License, [199] and [200]).

Fuel Cells

Technology Profiles

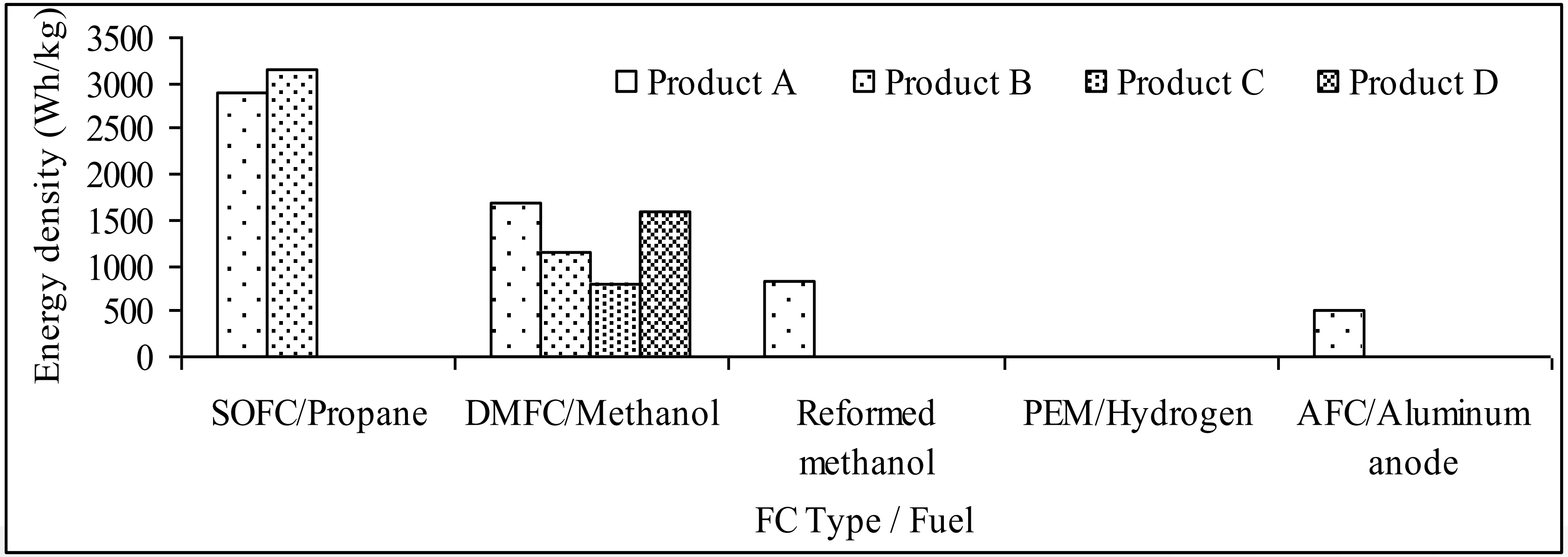
	PAFC	AFC	MCFC	SOFC	SPFC	DMFC
Operating Temperature (ºC)	150-210	60-100	600-700	900-1000	50-100	50-100
Power Density (W/ cm^2)	0.2-0.25	0.2-0.3	0.1-0.2	0.24-0.3	0.35-0.6	0.04-0.23
Projected Life (hrs)	40,000	10,000	40,000	40,000	40,000	10,000
Projected Cost (US$/KW)	**1000**	**200**	**1000**	**1500**	**200**	**200**

- Phosphoric Acid Fuel Cell (PAFC)
- Alkaline Fuel Cell (AFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)
- Solid Polymer Fuel Cell (SPFC)
- Direct Methanol Fuel Cell (DMFC)

Fuel Cells

Fuel Energy Density for Various Fuel Cell Technologies

- Fuel Cell Energy Density is not a straight forward process because of the packaging of fuel used
- According to various commercially available products
  - SOFC using propane fuel offer the highest energy densities
  - DMFC using methanol fuel offer the second highest energy densities



Super Capacitors

Technology Overview

- Super-Capacitors have the same characteristics as ordinary capacitors

$$I_c = C\frac{dV_c}{dt}$$

- Super-Capacitors have much higher capacitance than ordinary capacitors hence they store more energy

$$E_c = \frac{1}{2}CV_c^2$$

Super Capacitors

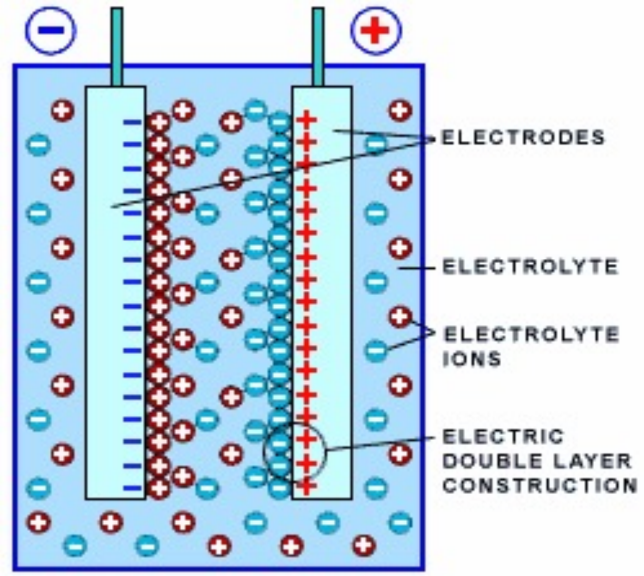
Energy Storage Mechanism

- The energy storage mechanisms divide super-capacitors to double layer and redox.
- Double layer super-capacitors store charge at the double layer interface between the electrodes and electrolyte, and capacitance is electrostatic.
- Redox super-capacitors, on the other hand, as implied by their name, store energy through a redox reaction.
  - This is a reversible process between multiple oxidation states in the electrode material, as in batteries, and give rise to what is called pseudo-capacitance [193], [199].

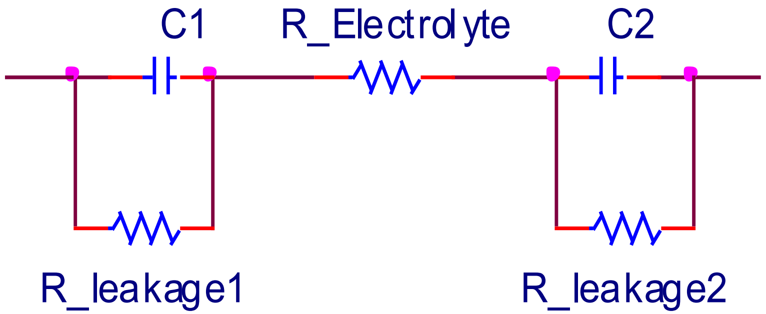
Super Capacitors

Block Diagram and DC Equivalent Circuit

- Double layer super-capacitors store charge at the double layer interface between the electrodes and electrolyte, and capacitance is electrostatic.
- The DC electrical model of the double layer super-capacitor – two capacitors in series with the electrolyte resistance.



Double Layer Super-Capacitor from [192], [194].



DC Electrical Model of a Double Layer Super-Capacitor from [191], [192].

Super Capacitors

Electrolytes

- Electrolytes for double layer super-capacitors can be organic or aqueous [192], [195].
- Organic electrolytes display lower capacitance values than aqueous electrolytes.
- In addition, organic electrolytes have operating voltage above 2.5V, while the voltage of aqueous systems is approximately 1.2V [194], [195].
- As a result of higher operating voltage, organic electrolytes provide a higher amount of stored energy which is directly proportional to the square of the voltage.
- On the other hand, organic electrolytes have higher ESR than aqueous electrolytes which limits the maximum output power of the device according to equation, $P = V^2 / R$.

Super Capacitors

Technology Overview

○ Super-Capacitors Advantages over Batteries

- higher power densities
- lower effective series resistance (ESR)
- higher efficiency
- lower RC time constant
- lower temperature dependency

Super Capacitors

Technology Overview

- Super-Capacitors Advantages over Batteries
  - higher power densities
  - lower effective series resistance (ESR)
  - higher efficiency
  - lower RC time constant
  - lower temperature dependency
- Super-Capacitor Disadvantages over Batteries
  - smaller energy density
  - higher cost

Super Capacitors

Technology Overview

- Super-Capacitors Advantages over Batteries
  - higher power densities
  - lower effective series resistance (ESR)
  - higher efficiency
  - lower RC time constant
  - lower temperature dependency
- Super-Capacitor Disadvantages over Batteries
  - smaller energy density
  - higher cost
  - Super-capacitors are not an attractive battery replacement so far

Super Capacitors

Characteristics of Commercially Available Products

Brand	Voltage (Volts)	Capacitance (Farads)	ESR (mΩ)		Energy Wh/Kg	Power W/Kg	Weight (gram)	RC Time Const. (Sec.)
			DC	AC				
Single Cell								
EPCOS	2.5	1800	0.6	0.3	2.9	2300	540	1.08
EPCOS	2.3	5	330	200	0.7	1200	5.5	1.65
NESS	2.3	20	55	40	3.7	6600	4	1.10
NESS	2.3	120	30	20	5.2	2600	17	3.60
Maxwell	2.7	2600	0.4	0.28	5.6	10400	470	1.04
Maxwell	2.5	2700	1	0.7	3.2	2.2	725	2.70
Skeleton	3	47	5.5	-	11.5	9600	5	0.26
MODULES								
EPCOS	14	200	5	2.6	1.9	1700	2800	2.50
EPCOS	42	67	15	8	2	1700	8200	1.01
NESS	5.4	1.5	200	150	1.74	10410	3.5	0.30
NESS	90	2.8	500	400	2.1	2800	1700	1.40
Maxwell	16.2	430	3.5	2.5	3.1	5200	5000	1.51

Super Capacitors

Characteristics of Commercially Available Products

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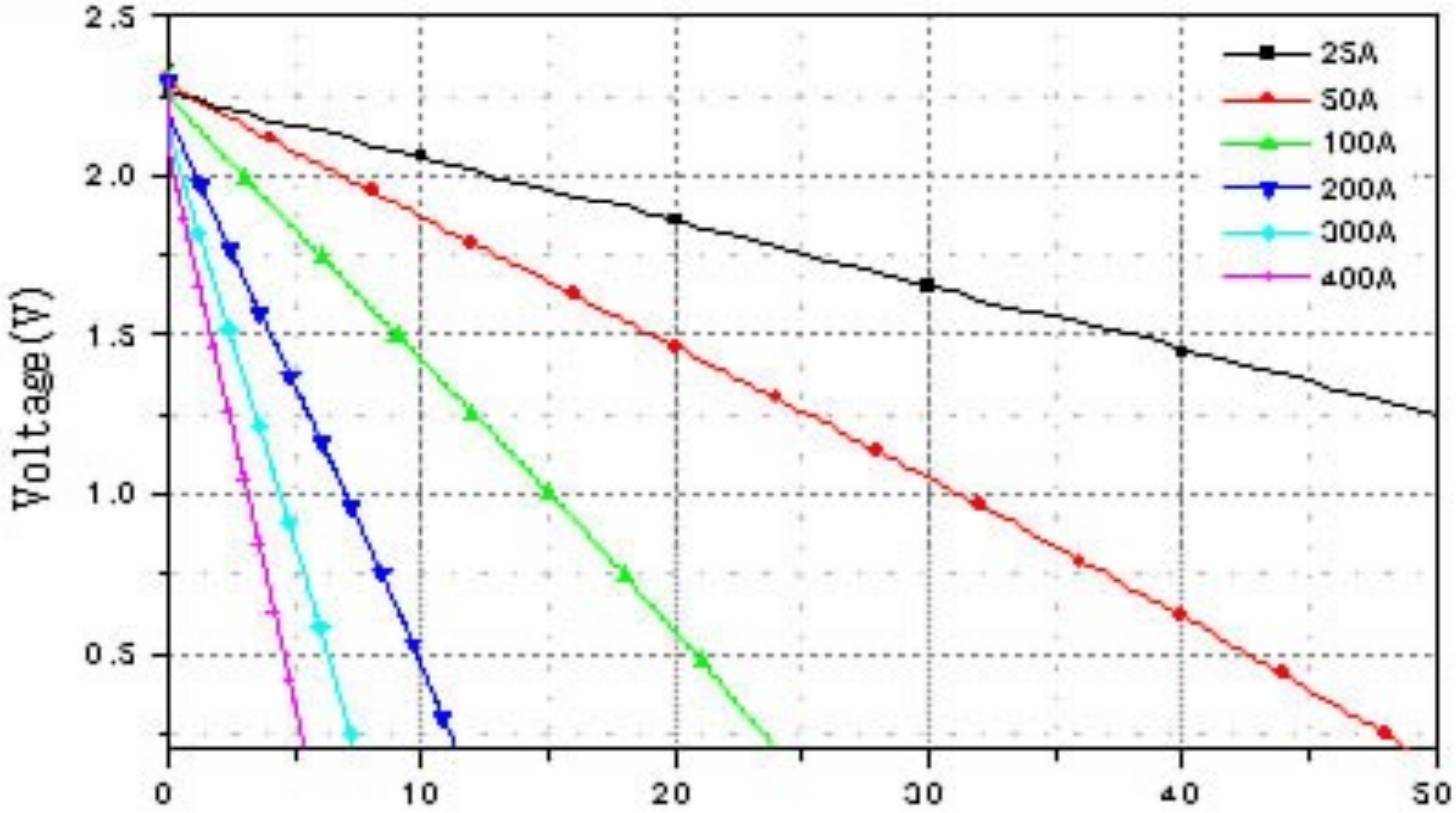
- Capacitance
  - Farads
- Power Density
  - kW/kg
- Time Constant
  - < 3s
  - Average ~1s

Super Capacitors

Current – Voltage Characteristics

- Can release all stored energy in a few seconds



Double Layer Super-Capacitor Constant Discharge Current Characteristics (NESSCAP1200P) from [201].

Battery and Super-Capacitor Combination

Technology Overview

- Super-Capacitor and Battery Combination
  - Super-capacitor provides high power density
    - *super-capacitor can supply short-term over- the-average power demand*
  - Battery provides a high energy density

- Configuration Advantages
  - prevents excessive over-sizing of the battery pack
  - higher battery efficiency
  - higher battery life

Battery and Super-Capacitor Combination

Technology Overview

- ○ The battery and super-capacitor combination is known as “hybrid system”
- ○ Two major configurations
  - Passive
  - Active
- ○ A passive system
  - is the direct parallel connection between the battery and the super-capacitor.
  - This configuration is very simple and keeps the cost to minimum since no other parts are required.

the voltage is not regulated, it follows the battery discharge curve and since it can vary significantly between fully charged and discharged then the super-capacitor full energy capab

Battery and Super-Capacitor Combination

Technology Overview

- A passive system
  - Direct parallel connection between the battery and the super-capacitor.
- Advantages
  - Very simple
  - Minimal cost since no other parts are required
- Disadvantages
  - the power sharing is determined by the ESR of the battery and the super-capacitor
    - *during pulsed operation the battery current can have high ripple values which may activate some internal protection schemes common in lithium-ion technology batteries resulting in shutting off of the battery*
  - the voltage is not regulated
    - *it follows the battery discharge curve and since it can vary significantly between fully charged and discharged then the super-capacitor full energy capabilities cannot be utilized*

the voltage is not regulated, it follows the battery discharge curve and since it can vary significantly between fully charged and discharged then the super-capacitor full energy capab

Battery and Super-Capacitor Combination

Technology Overview

- Active System
  - A DC to DC converter is connected between the battery and the super-capacitor
- Advantages
  - Adding the DC to DC converter between the battery and super-capacitor configuration can eliminate all the negative effects mentioned for the passive configuration.
  - In addition the super-capacitor voltage can be different from the battery voltage, thus giving more design flexibility [202]
  - the DC-DC converter can act as a battery charging regulator while the passive system would require a separate battery charger
  - Research reported that and active hybrid system has 3.2 times higher peak and 2.7 times higher specific energy than a passive system. F
  - Lower battery currents with smaller ripple, than the passive system which results in a lower battery temperature and longer battery lifetime.
- Disadvantage
  - Due to the added converter and increased super-capacitor losses, an active system has less discharge cycle time than a passive system.

Pumped Storage Hydro Power

Technology Overview

- The power of water (hydro derived from the Greek word ὕδωρ) has been one of the main RES since 1900s.
- However, the power derived from the energy of falling or fast-running water has been harnessed since the ancient times using different kinds of watermills for useful purposes including irrigation and the operation of various mechanical devices, such as gristmills, sawmills, textile mills, trip hammers, dock cranes, domestic lifts, and ore mills

Moulin Banal in Braine-le-Chateau, Belgium Dating from the 12th Century (Credit: Pierre (Pierre79) , Wikimedia Commons author (GNU Free Documentation License - public domain) [203])

Pumped Storage Hydro Power

Technology Overview

- The hydro electric technology is now matured and well understood
- Advancements in engineering and manufacturing has led to the development of mega-dams capable with reservoirs big enough to power entire cities and countries
- However, mega-dams affect the environment and ecosystem; divert and reduce natural river flows, thus restricting access for animal and human populations.

Itaipu Hydro Electric Dam (Credit: Jonas de Carvalho – Flickr licenced under CC BY-SA 2.0, [204])

Pumped Storage Hydro Power

Environmental Impact

- Some of the mega-dams significantly affect the visual landscape
- Smaller hydro electric dams do not affect the landscape in such a great extend
- Pumped storage hydro electric dams are usually smaller in size.

Three Gorges Hydro Electric Dam in China (Credit: Le Grand Portage licenced under CC BY 2.0, [205])

Goldisthal Pumped Storage Hydro Electric Dam in Germany (Credit: Voith under Written Permission, [206])

Pumped Storage Hydro Power

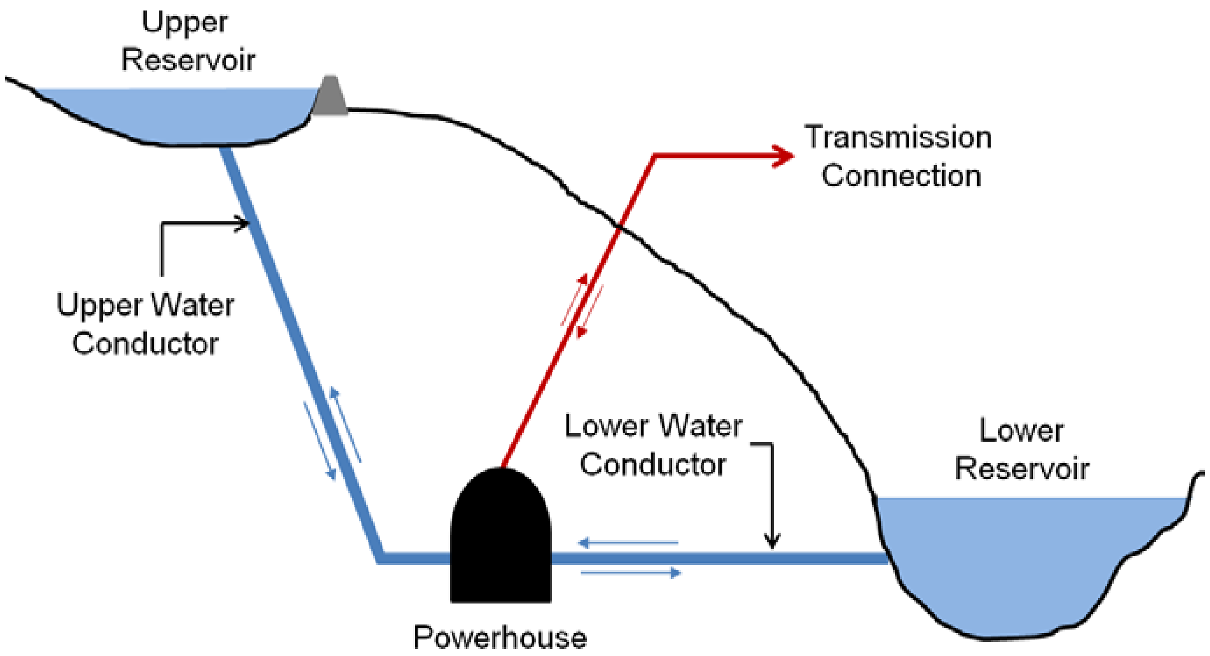
Technology Overview

- Hydropower is the most stable and predictable RES compared to wind and solar.
- Due to the storage capabilities, dams, reservoirs and lakes, hydropower offers high controllability and dispatchability.
- According to research [207] in 2019, 12% of European Union's electricity was generated by hydropower.
- This percentage is equivalent to a 36% of the total RES combined generated power.

Pumped Storage Hydro Power

Technology Overview

- Components
  - Upper Reservoir
  - Lower Reservoir
  - The water channel is also known as conductor and penstock.
- During peak hours water flows from the upper reservoir to the lower thus producing electricity
- During off-peak hours water from the lower reservoir is pumped back up to the upper reservoir



Typical Pumped Storage Configuration [210].

Pumped Storage Hydro Power

Technology Overview

- The process of generating electricity using hydropower is simple. Because of elevation difference then water flows downhill thus converting potential energy to kinetic.
- Then the kinetic energy is converted to mechanical by rotating the turbine which in turn rotates a generator producing electricity. This process is best described by the mathematical Equation:

$$P = \eta \rho g Q H$$

where

- P is the power in watts
- η is the efficiency (micro – 50-60%, small > 80%)
- ρ is the density of water (1000 kg/m3)
- g is the acceleration due to gravity (9.81 m/s^2)
- Q is the flow passing thru the turbine (m^3/s)
- H is the head or drop of water (m)

Pumped Storage Hydro Power

Classification

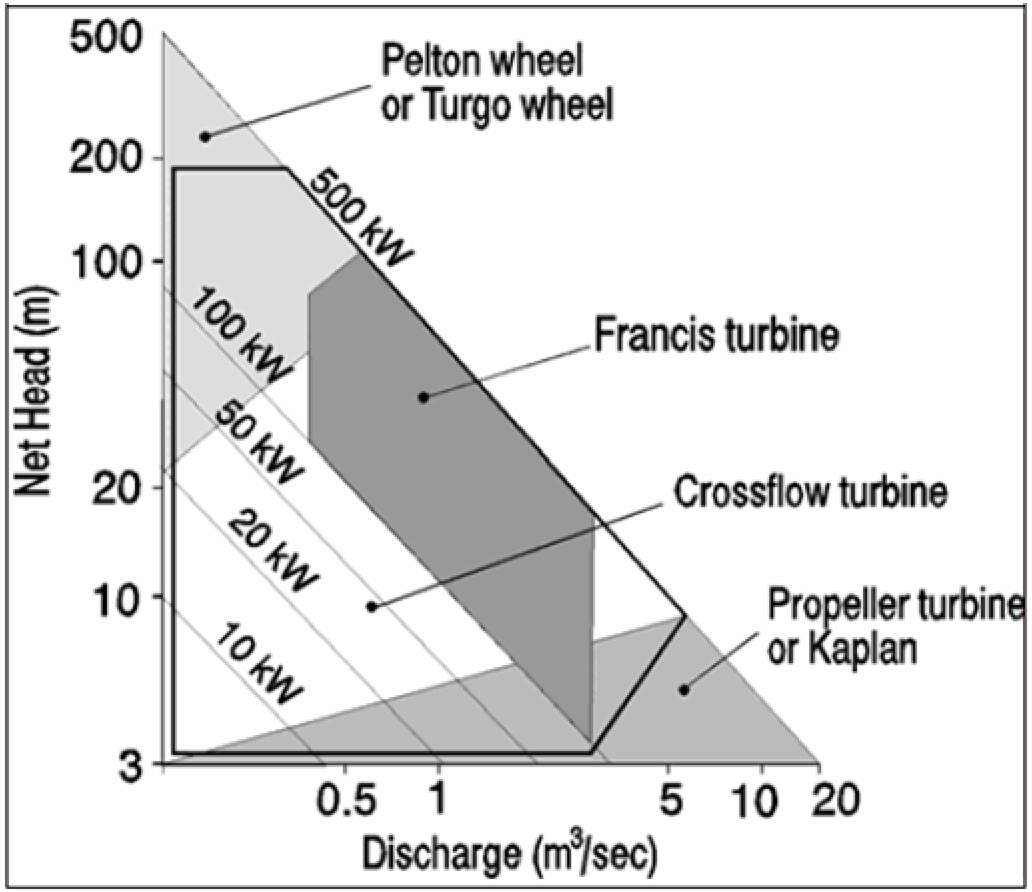
- Hydropower dams are classified according to their output power generation
  - Micro between 0.1 to 1 MW
  - Small between 1 to 50 MW

- Efficiency#
  - Micro hydropower is between 50 and 60%
  - Small it exceeds 80%

Pumped Storage Hydro Power

Technology Overview

- The power generation is a function of water discharge and the size of the head.
- As research shows these two parameters are critical in the selection of the turbine to be used.
- The range of turbines includes the Francis, Crossflow, Kaplan and Pelton or Turgo wheel.
- These turbines fall in two categories; reaction and impulse.



Head-flow Range of Small Hydro Turbines [208], [209].

Pumped Storage Hydro Power

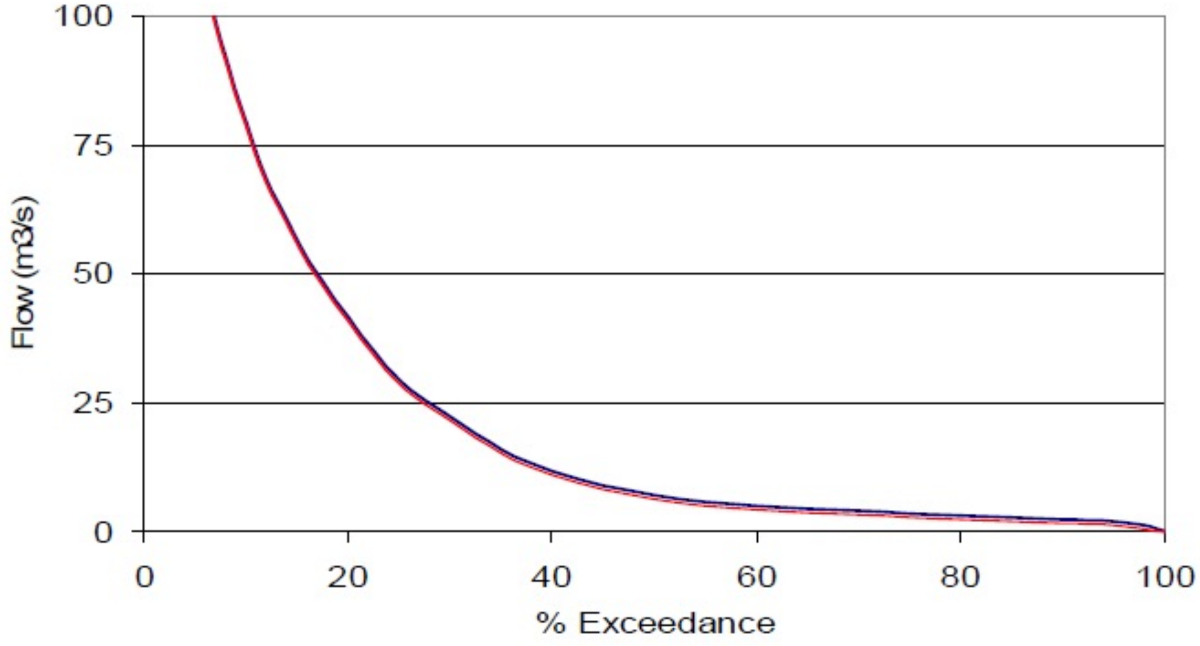
Technology Overview

- Impulse turbines such as Pelton, Turgo and cross flow turbines, are driven by high-velocity water jets.
- On the other hand, reaction turbines such as Kaplan and Franscis, have their rotors fully immersed in water and enclosed in pressure casings which creates pressure differences and lift forces which enables the runner blades to rotate very fast.
  - Research has shown that the runner blades of reaction turbines are able to rotate faster than their counterparts used in aircraft jets.

Pumped Storage Hydro Power

Technology Overview

- The power generation from pumped storage hydropower is controlled by controlling the water flow.
- Some useful industry terminology includes the flow and power duration curves which are depended on the percentage exceedance.
- The % exceedance represents the water flow variability and probability.
- The minimum flow is shown as 100% exceedance whereas maximum with 0%.

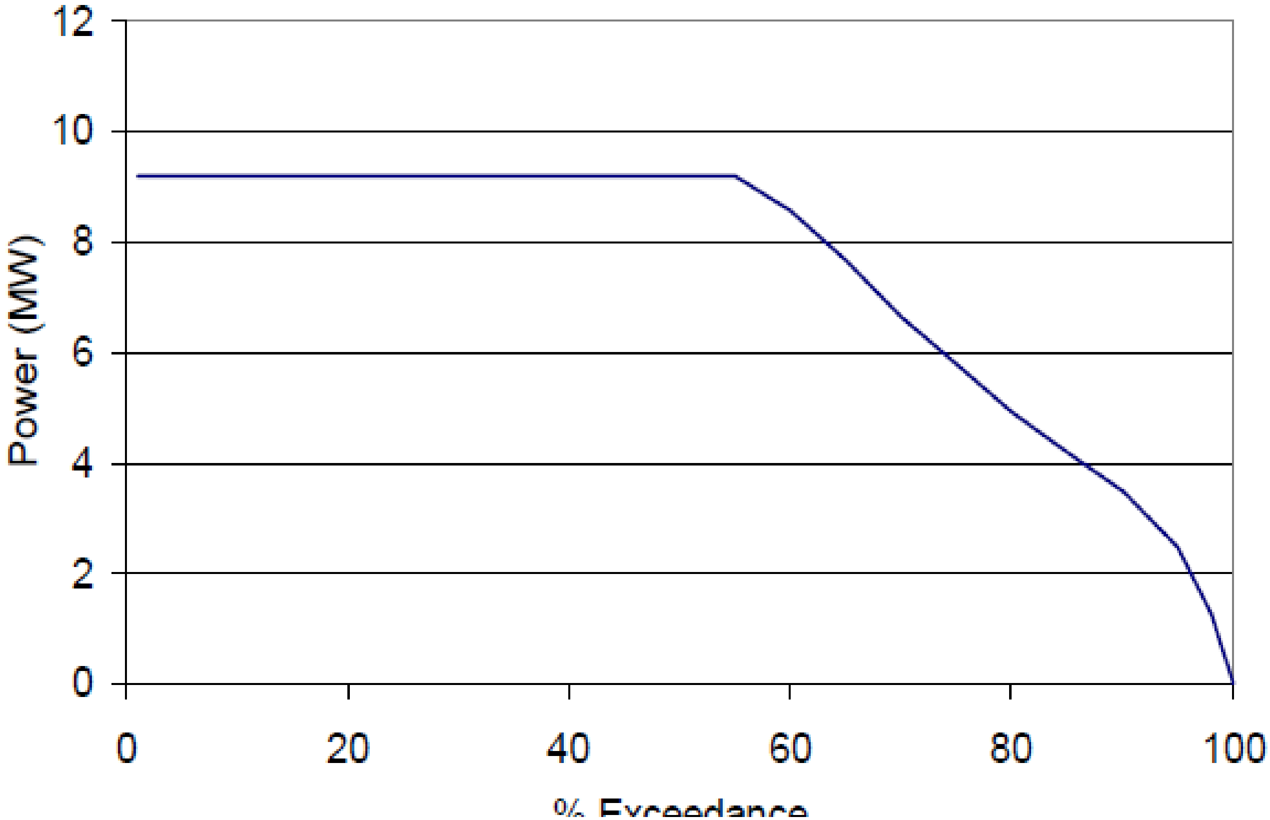


Flow Duration Curve [208], [209].

Pumped Storage Hydro Power

Technology Overview

- Maximum power is generated with exceedance lower than 60%

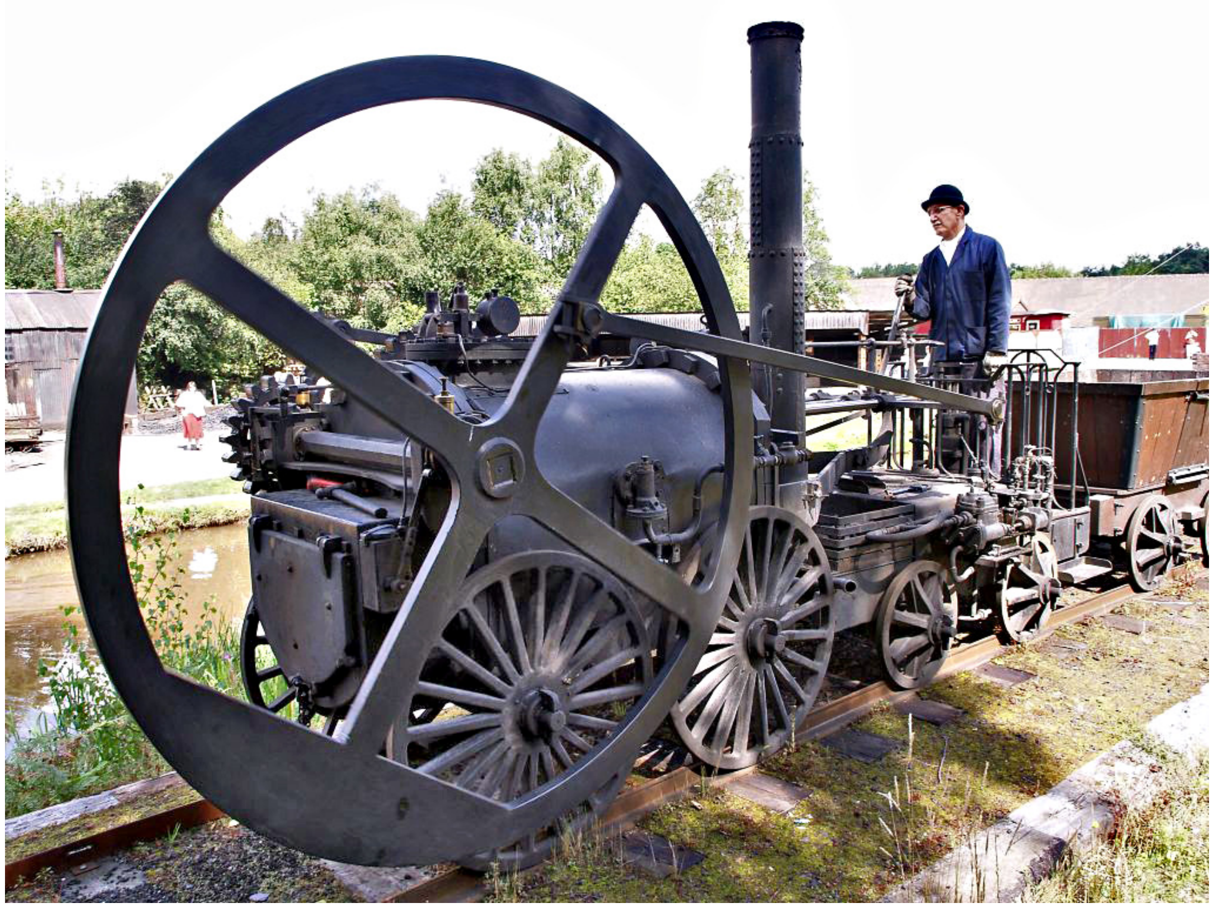


Power Duration Curve [208], [209].

Flywheel Energy Storage Systems

Technology Overview

- Flywheels are mechanical systems which store energy in the form of kinetic energy.
- This energy is proportional to the moment of inertia and angular velocity of the rotating wheel.
- Flywheels come in all circular shapes and sizes.
- Applications of flywheel systems range from traditional locomotion, industrial size energy storage, automotive and racing.



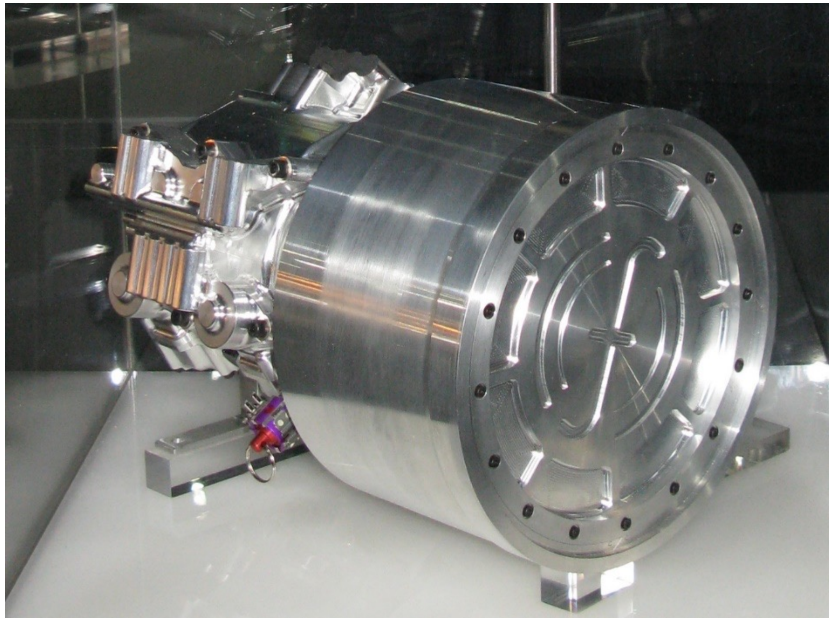
Trevithick's 1802 steam locomotive(Credit: Birmingham Museums Trust licenced under CC BY-SA 4.0, [211])

Flywheel Energy Storage Systems

Technology Overview

- An industrial size, commercially available flywheel energy storage system which is used for wind farms and public transportation applications.
- An example of regenerative energy used in formula 1 racing, where the flywheel stores energy when the car is braked, allowing it to be recycled to accelerate the car later.

Flywheel system for wind farms and public transport (Credit: STORNETIC GmbH [212])

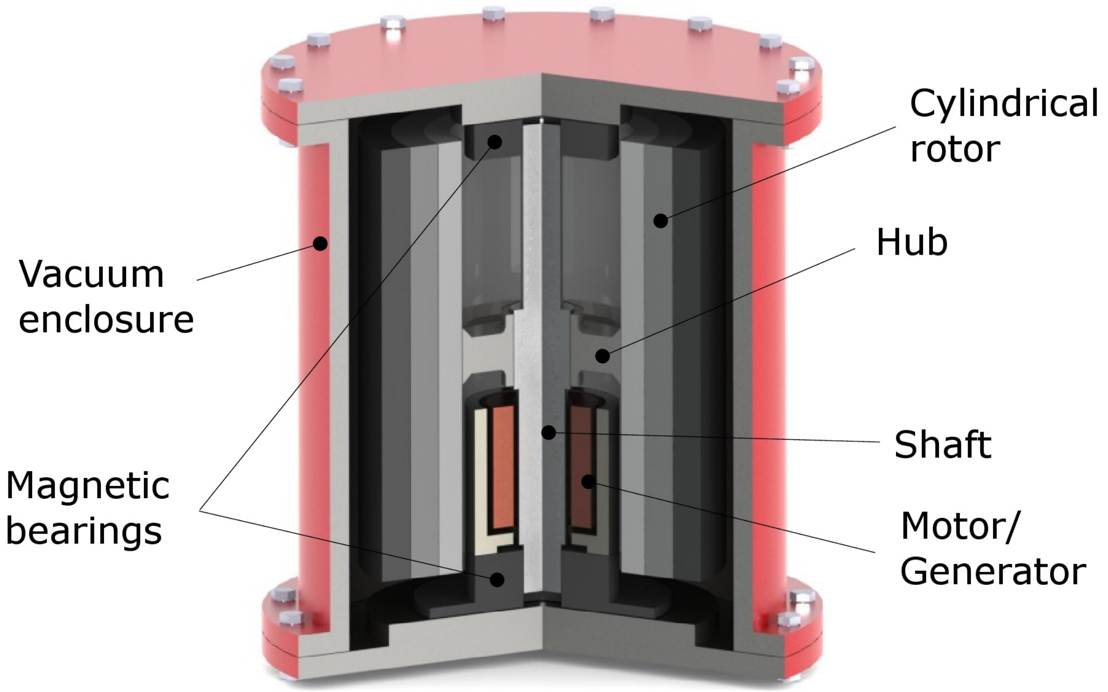


A Flybrid Systems Kinetic Energy Recovery System built for use in Formula One (Credit: Geni licensed under GFDL CC-BY-SA [213])

Flywheel Energy Storage Systems

Technology Overview

- A flywheel is composed of the rotor which provides and mass and moment of inertia, the hub or shaft that connects the rotational movement to the motor or generator. All these are enclosed in vacuum to eliminate the losses due to air resistance and for higher efficiency magnetic bearings are used that eliminate the friction losses.



The main components of a typical cylindrical flywheel rotor assembly (Credit: Pjrensburg under GNU Free Documentation License [214].

Flywheel Energy Storage Systems

Technology Overview

- The moment of inertia of the cylindrical rotor **$J=mr^2$**
  - Where J is the moment of inertial measured in kgm^2, m is the mass in kg and r is the radius in m.
- The stored kinetic energy is best described by **$E_k=1/2\,J\omega^2$**
  - Where E_k is the kinetic energy in Joules (J) and ω is the angular velocity in rad/s.

Flywheel Energy Storage Systems

Technology Overview

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- The stored kinetic energy is best described by **$E_k=1/2\,J\omega^2$**
  - Where E_k is the kinetic energy in Joules (J) and ω is the angular velocity in rad/s.
- Note:
  - The faster the rotor spins then the higher amount of energy is stored in the flywheel.
  - The maximum theoretical stored energy depends on the material used.
  - When the maximum energy is exceeded then the device shutters.
  - This is because of the tensile strength of materials.

Flywheel Energy Storage Systems

Technology Overview

- The tensile strength of materials.

$$\sigma_t = \rho r^2 \omega^2$$

  - Where σ_t is the tensile stress on the rim of the cylinder in joules, ρ is the density of the cylinder, r is the radius of the cylinder and ω is the angular velocity of the cylinder.

- According to the handbook of mechanical alloy design [215] ceramics offer the highest specific tensile stress of approximately 2000kJ/kg but they are weak and brittle hence cannot be used for this application. On the other hand, cast iron is very strong but its specific tensile stress is only 8kJ/kg. The composite carbon-fibre (500kJ/kg) provides the best performance with respect to strength and cost thus offering the highest flywheel efficiency.

Flywheel Energy Storage Systems

Technology Overview

- The output power of the flywheel equals to the output power of the connected machine. For example, in the case of a synchronous machine

$$P = V_i V_t \left(\frac{\sin(\delta)}{X_s}\right)$$

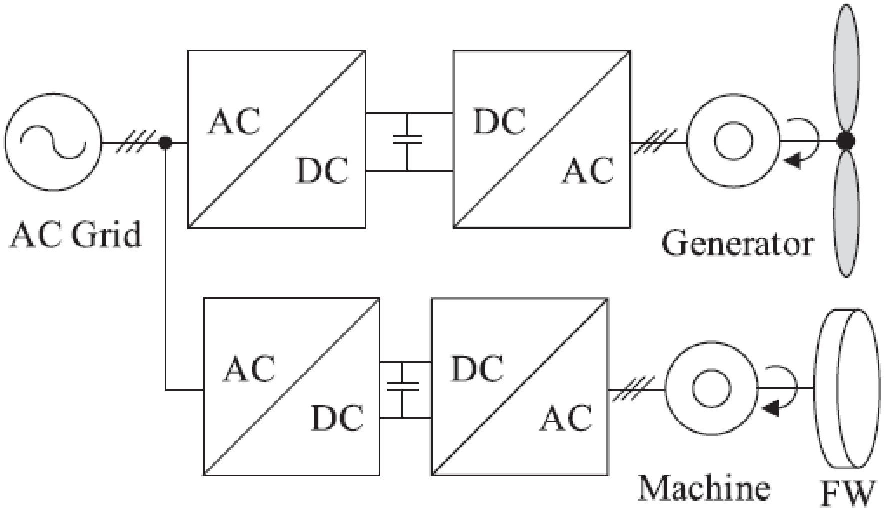
- Where V_i is the voltage of rotor winding which is produced by field interacting with the stator winding, V_t is the stator voltage, δ is the torque angle also known as the angle between two voltages, and X_s is the stator reactance.

- Flywheel storage systems are typically small with peak power capability is the range of 20 MW.

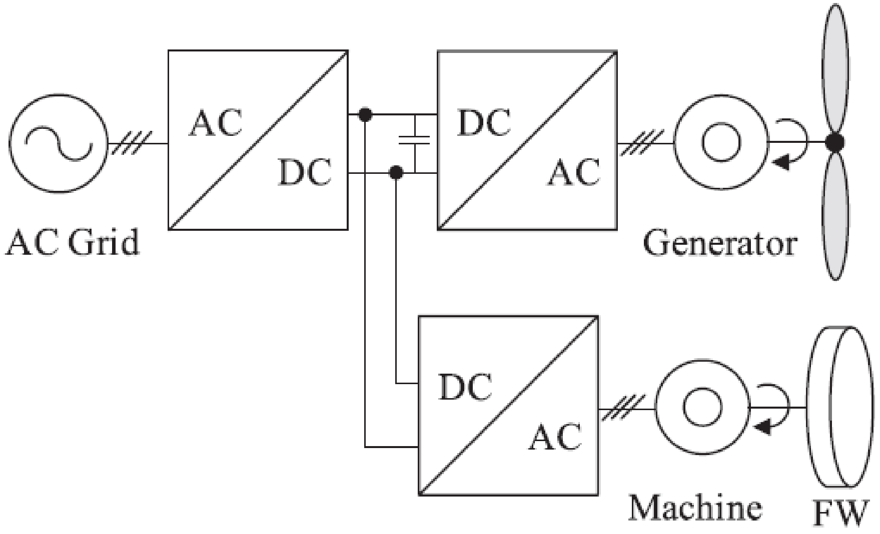
Flywheel Energy Storage Systems

Technology Overview

- Flywheels can be connected directly on the grid or connected on a DC link.
- In both cases back to back bidirectional converters are required.



Back to Back DC-AC connected directly to the grid.



Back to Back DC-AC converter connected in DC-link.

Compressed Air Energy Systems

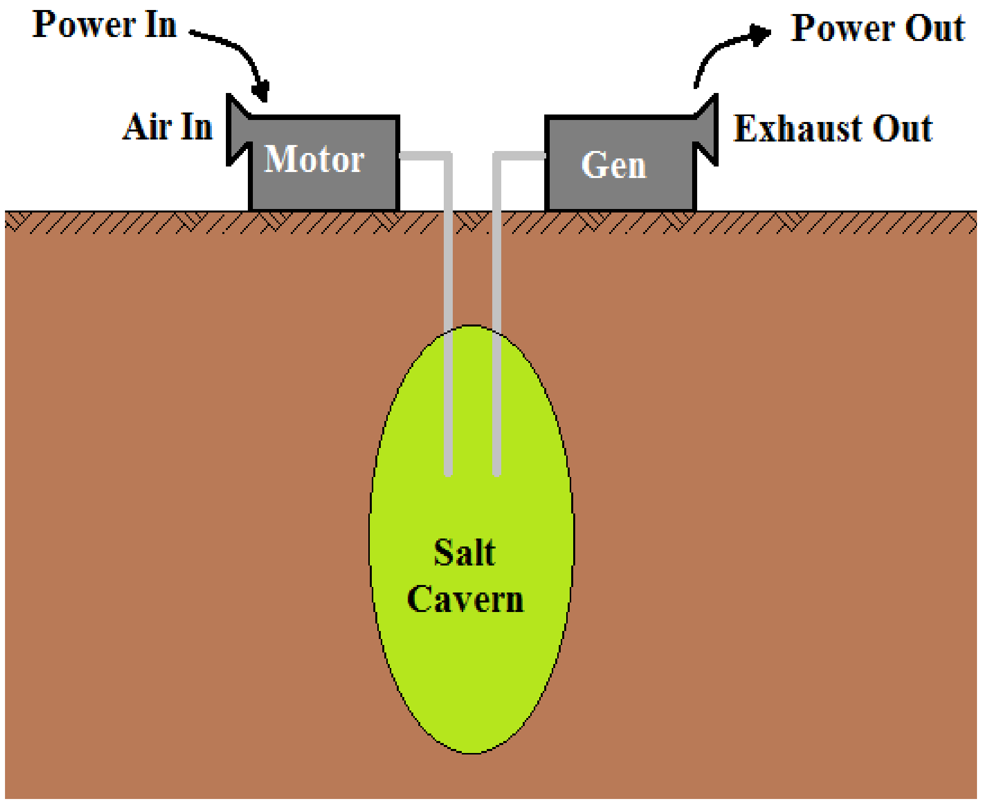
Technology Overview

- Compressed air energy systems (CAES) like all other energy storage systems convert electrical energy during off-peak hours to other forms of energy.
- In the case of CAES electrical energy is converted to pressurised gas which is stored in compressed air reservoirs.
- When the gas is in small quantities then it is stored in metal containers whereas when it is in bigger quantities then it is stored in underground salt cavern.
- During peak hours, the pressurised air is released (expand / decompressed) through a generator which produces electricity.

Compressed Air Energy Systems

Technology Overview

A pressurized air tank used to start a diesel generator set in Paris Metro (Credit: F1jmm under licence CC BY-SA 3.0 [219]).

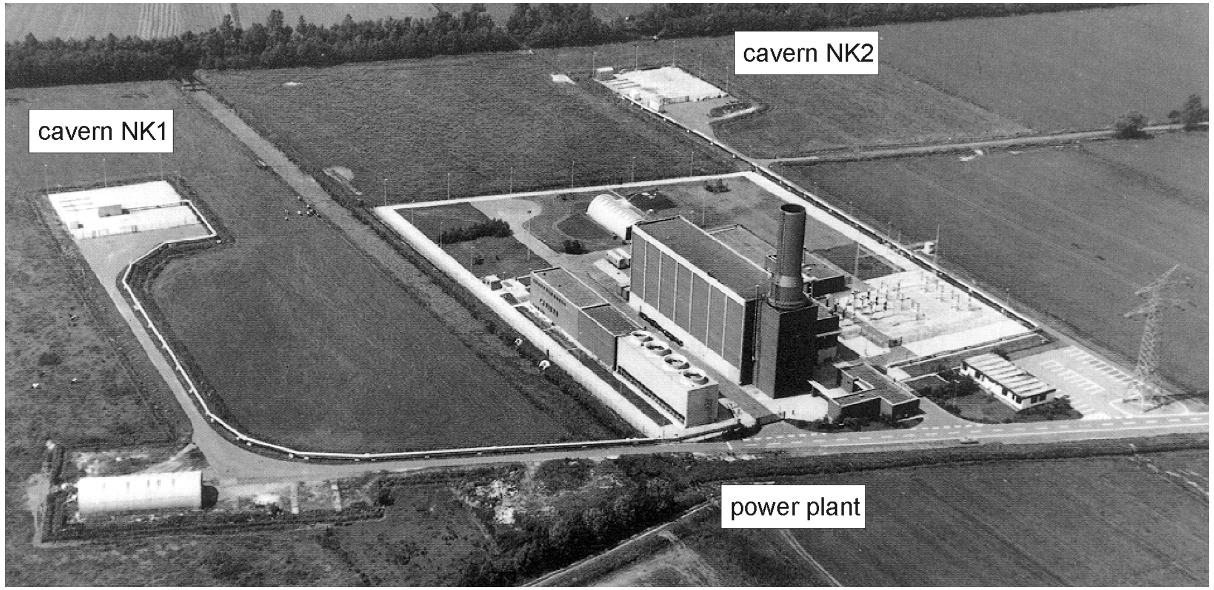


CAES using underground salt cavern (Credit: Lee Layton, PE, and www.PhDOnline.com, under Written Permission [222]).

Compressed Air Energy Systems

Technology Overview

- The process of compressing and decompressing the air introduces a lot of losses (heating and cooling of the gases) resulting in round trip efficiencies of 65 to 75%.
- Large CAES have higher losses hence lower efficiency compared to smaller scale CAES.
- According to literature [220], [221], [222], CAES date back to the 1870s in big European and Latin America cities for the purpose of powering machinery.
- Furthermore, in 1896 a 2.2 MW CAES system served the industry in Paris. The system's air pipes were distributed over 50 km at an operating pressure of 550 kPa.
- More recently,
  - 1978 a 290 MW plant was build in Huntorf, Germany
  - 1991 a plant of 110 MW peak power and 26 hours duration was built in McIntosh, Alabama, USA.
  - Both plants are operational to this day



Aerial picture of Huntorf plant (Credit: F. Crotogino, et.al, and Solution Mining Research Institute (SMRI), under Written Premission [225], [235]).

Compressed Air Energy Systems

Technology Overview

- Compressed Air Energy System refers to the process of compressing and storing air under high pressures in containers.
- The compressing of the air can be achieved using compressors or turbines whereas the generation of electricity is with the use of generators.
- The storage containers fall under two categories: constant volume and constant pressure.
  - Mine caverns, aquifers and automotive are examples of constant volume storage
  - Underwater pressure vessels and Hybrid Pumped Hydro - Compressed Air Storage are examples of constant pressure.
- The process of compression creates heat which causes the compressed air to be warmer, whereas expansion removes heat causing the expanded air to be colder.
- CAES handle these issues by varying the thermodynamic conditions of the storage technologies. The three main thermodynamic processes used are adiabatic, diabatic and isothermal (or near-isothermal).

Compressed Air Energy Systems

Technology Overview

- The amount of energy stored is best described using the isothermal (also known as reversible) process under the assumptions that the compressed air obeys the ideal gas law and that the temperature remains constant.

$$pV = nRT$$

- Where *p* is measured in pascals, *V* is measured in cubic metres, *n* is measured in moles, and *T* is the absolute temperature in kelvins. The ideal gas constant, *R*, is the product of the Boltzmann's constant and the Avogadro's constant which yields a value of 8.314 J/(K·mol). The absolute temperature is 0 K which is equivalent to -273^{o}C. Therefore, it can be said that for the isothermal process

$$pV = nRT = constant$$

Compressed Air Energy Systems

Technology Overview

- The amount of work from an initial state A to a final state B is calculated

$$W_{AB} = \int_{V_A}^{V_B} p dV = \int_{V_A}^{V_B} \frac{nRT}{V} dV$$

- Which can be rewritten as

$$W_{AB} = p_B V_B ln \frac{p_A}{p_B} + (p_B - p_A) V_B = p_A V_A ln \frac{p_A}{p_B} + (V_A - V_B) p_A$$

Compressed Air Energy Systems

Technology Overview

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- For example:
  - in a storage vessel of 1 m^3 at a pressure of 70 bars (7.0 MPa) and an ambient pressure is 1 bar (0.10 MPa) it is calculated that the stored energy comes to -22.8MJ.
  - The negative sign indicates that work is done on the gas by the surroundings. This amount of energy distributed over a period of 1 hour or 3600 seconds is equivalent to 6.33 kWh.

Compressed Air Energy Systems

Technology Overview

- During the charging process, the compressor consumed electric power is given by:

$$P = \frac{kQR_{gas}T_{in}}{(k-1)\eta_c}\left(\beta^{\frac{\kappa-1}{\kappa}} - 1\right)$$

- Where P is the compressor’s consumed power, k is the adiabatic exponent, η_c is the compressor efficiency, Q is the mass flow rate of air, R_{gas} is the air gas constant, T_{in} is the air temperature entering the compressor’s inlet and β is the compression ratio.

- In addition, the air temperature exiting the outlet can be expressed as:

$$T_{out} = T_{in}\left(\frac{\beta^{\frac{\kappa-1}{\kappa}} - 1}{\eta_c} + 1\right)$$

Compressed Air Energy Systems

Discussion and Conclusions

Technology	Peak Power	Energy	Round Trip Efficiency	Discharge Time	Lifetime / Cycles	Cost
	(MW)	(MWh)	(%)			(€/kWh)
PHPS	100-4,000	10,000	65-80	1-24 h	30-40 years	35-70
CAES	50-300	5,000	65-75	1-24 h	30 years	10-70
Battery	50	500	75-90	s - h	10^3-10^4 cycles	70-4,000
Hydrogen	50	N/A	20-50	14-24 h	10^4 hours	2,000-15,000
SMES	0.1-10	1,000	80-90	ms - s	10^6 cycles	200-500
Flywheel	0.75-10	5	80-90	ms - s	10^6 cycles	140-350
Supercapacitors	0.1-10	3	90-95	ms - m	10^6 cycles	70-400

Compressed Air Energy Systems

Discussion and Conclusions

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Supercapacitors	0.1-10	3	90-95	ms - m	10^6 cycles	70-400

- As can be seen the energy storage technologies can serve a wide range of needs, ranging from peak power, to energy, to response time from milli-seconds to hours.
- According to the required specifications then the selected technology will have the equivalent cost

Compressed Air Energy Systems

Discussion and Conclusions

Technology	Toxic material	Flammable	Rare Metal	Moving part
Flow Battery	Yes	No	No	Yes
Liquid Metal	No	Yes	No	No
Sodium ion	No	Yes	No	No
Lead-Acid	Yes	No	No	No
Na-S Battery	Yes	No	No	No
Ni-Cd	Yes	No	Yes	No
Lithium-Ion	No	Yes	No	No

Compressed Air Energy Systems

Discussion and Conclusions

Technology	Toxic material	Flammable	Rare Metal	Moving part
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- The Lithium battery chemistry has become the preferred choice because it offers high power and energy density, and also it is non-toxic, lithium is not a rare material, has no moving parts which entitles minimal running costs.
- The only drawback that lithium batteries have is that they are flammable. However, using the correct safety electronics then this is overcome.

- The aim of Section II is to introduce the students with the various energy storage systems (technology overview) and their technical characteristics (performance metrics).
- Technologies under consideration include Batteries, Fuel Cells, Super-Capacitors, Hybrids (Battery and Super-Capacitor Combined), Pumped Storage Hydropower, Flywheels and Compressed Air Energy Systems.
- As discussed the energy storage technologies can serve a wide range of needs, ranging from peak power, to energy, to response time from milli-seconds to hours.
- According to the required specifications then the selected technology will have the equivalent cost

Summary

Energy Storage Systems are of vital importance for the Smart Grid

Thank You

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Introducing Recent Electrical Engineering
Developments into undErgraduate cuRriculum

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Introduction to Renewable Energy

Lecture 12: Off-grid/ Stand-alone Systems

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Introducing Recent Electrical Engineering
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This week's topics…

- Off-grid Systems
- Stand-alone Systems
- Mini-grid System
- Hybrid Systems

Section Outline

In this section, the general definitions about off-grid, stand-alone and mini-grid systems of electrification will be explained

Section 1

Off-grid Systems

Off-grid Systems

Stand-alone systems and Mini-grid Systems

- Providing electricity access has two general approaches: the former is by extending the public electricity grid and the later is by implementing off-grid systems.
- Grid extension is the default electrification service by the governments and its utilities.
- About 99% of electricity infrastructures investments go toward grid extension projects.
- Off-grid systems are only considered when there is a compelling reason not to extend the grid to a certain community

Off-grid Systems

Stand-alone systems and Mini-grid Systems

Reasons to not include grid extension:

- Off-grid systems are less expensive on the basis of per-unit or per-connection.
- The wait for grid extension connecting is too long.
- The electricity access tier provided by the grid is insufficient for the community.
- The cost of grid extension electrification is directly proportional to the distance between the desired place and the grid. The off-grid cost does not depend on the distance. This is a good reason to use off-grid solutions.

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- Off-grid is a system and lifestyle designed to help people and communities function without the support of remote infrastructure.
- In electricity, off-grid includes stand-alone systems and mini-grid systems.

Off-grid Systems

Stand-alone systems and Mini-grid Systems

- Off-grid electrification is accessing and using electricity locally without the need to use the public utility grid.
- This makes certain communities live in a self-sufficient style regarding the usage of utility grids.
- In civilian societies, most important needs for people reach them using utility grids.
- The most important needs recently are water and electricity.
- There are several hard-to-reach sites that have many difficulties to obtain the services of utility grids.

Off-grid Systems

Stand-alone systems and Mini-grid Systems

- Many rural areas and islands are far away from the utility grids and the electrification for these areas is costly and has many technical difficulties.
- The optimal solution is to use the local renewable source to electrify the private and community buildings.
- The optimal solution is to use the local renewable source to electrify the private and community buildings.
- About 14% of the world people do not access to electricity and the off-grid systems represent one choice of the realistic solutions to those people.

Stand-alone systems

- When the electrical power is generated and used in same site, this system is called stand-alone system.
- The stand-alone power system (SAPS, SPS or RAPS) is one type of off-grid system which is used for far away locations.
- The generated electrical power may be transmitted directly to the load or it may be stored in batteries to be then used to function the loads later on.

Off-grid Systems

Stand-alone systems

- The generation of electrical power may be obtained using two main types of electricity generation.
- The power generation using the conventional sources and the power generation of renewable sources.
- The first type includes the usage of the well-known fuel generators.
- The second type includes solar, wind and hydro generators among others.
- Most of stand-alone power systems use battery banks to store power.

Off-grid Systems

Stand-alone systems

- The direct output power that is directly used from batteries is DC which could be used for lighting and for DC appliances.
- Usually an inverter is used to convert DC to AC voltage which is used mostly in normal appliances.
- The stand-alone system may be divided into three types: the Pico system, the home system and the productive system.

Pico System

- This type of power systems is the smallest among the others mentioned.
- It is used for function individual appliances like light bulbs, televisions and radios.
- Pico system is very cheap and very easy to install.
- Also, it does not take big area or long time to install

Home System

- This type of power systems is medium in power, size and cost.
- It can be used to supply power to certain household.
- All the home appliances could be powered and work normally using this system of supplying power.
- All appliances used for civilian needs that are dependent on electrical power will have sufficient power to work

Productive System

- This type of power systems is the largest in power, size and cost among all types of stand-alone systems.
- It can be used to supply power to certain big independent stand-alone single unit like factory, hotel, clinic or farm.

Stand-alone System

Applications

- Any place that is far away from the electrical utility grid and need to be supplied by electricity can use the stand-alone systems.
- Many applications can use this type of power providing which generate the power locally.
- Some of the most well-known applications are:
  - Villages in remote areas.
  - Private homes and offices.
  - Microwave/Radio repeater stations.
  - Medical facilities in rural areas.

Stand-alone System

Applications

- Emergency communications.
- Water quality and environmental data monitoring.
- Drinking water and livestock water pumping.
- Irrigation pumping.
- Aviation obstruction lights.
- Environmental data monitoring.
- Railway signals.
- Street lighting.
- Desalination.

Stand-alone Solar System

Components

- Solar modules.
- Batteries.
- Bi-directional inverters.
- Transformers.
- Power distribution panels.
- Metering devices.
- Solar charge controller.

Stand-alone Solar System

Battery Charging

- The solar panel or module produces DC electricity which is charging the storage batteries via a solar charge controller.
- All DC appliances that are connected to the battery must be fused (using fuses to protect its).
- The lights that are operated by DC are normally connected to the charge controller.
- To operate the AC appliances, they are connected to the inverter which is directly connected to the battery.
- Stand-alone system voltages are typically from 12V DC to 48 V DC. For larger systems, the voltages are from 400 V DC to 800 VDC.

Stand-alone Solar System

Battery Charging

- The generated DC voltage of the solar panel must be higher than 12 V DC to charge the battery of 12 VDC.
- Normally, a voltage of 14.4 V DC generated using solar panel can charge the battery of 12 V DC.
- When the solar cells operate at a high temperature, a solar panel must provide a voltage of about 20 V DC to charge the battery properly.
- To protect the battery and ensure it has long life to work without reducing the system efficiency, a charge controller is used.

Stand-alone Solar System

Battery Charging

- To protect the battery from over-discharge, the charge controller disconnects the battery from the load.
- This operation is called low voltage disconnect (LVD).
- Similarly, to protect the battery from over-charge, the charge controller disconnects the battery from the charger.
- This operation is called high voltage disconnect (HVD).
- Furthermore, the charge control protect the solar panel from the flowing back current (reverse current) that might be flow back during night.

Stand-alone Solar System

Design Procedure

- Determining how much electricity is needed by calculating the load in daily or weekly basis.
- Determining the battery type regarding the storage capacity in Ah that is enough to the real needs.
- Calculating how much sun the desired site receives monthly taking into account the month of least sun and more demand.
- Approximating the array size depending on the worst month regarding sun shining.

Mini-grid System

Definition

- A mini-grid is an off-grid system that is isolated from the public utility grid.
- This system has a small distribution grid that supplies power to a limited numbers of consumers.
- This type of systems has additional names like micro-grid and isolated grid.
- The wattage generated normally in this type ranged from 10 KW to 10 MW.
- The mini-grid may provide power to small residential villages, small technical workstations and group of shops.

Mini-grid System

clean energy mini-grids

- Mini-grids that depends on renewable energy is called clean energy mini-grids (CEMGs).
- It depends on one or more types of renewable energy sources like solar, wind and hydro.
- The basic function of a mini-grid is to produce electricity and distribute it to users in a limited geographical area.
- Mini-grids can be divided into three systems:

  - Energy production.

  - Energy distribution.

  - End use.
- Most of the components related to energy production are located inside the power house.
- The components of the distribution system are connecting the energy production system to the end users using overhead lines or underground lines.

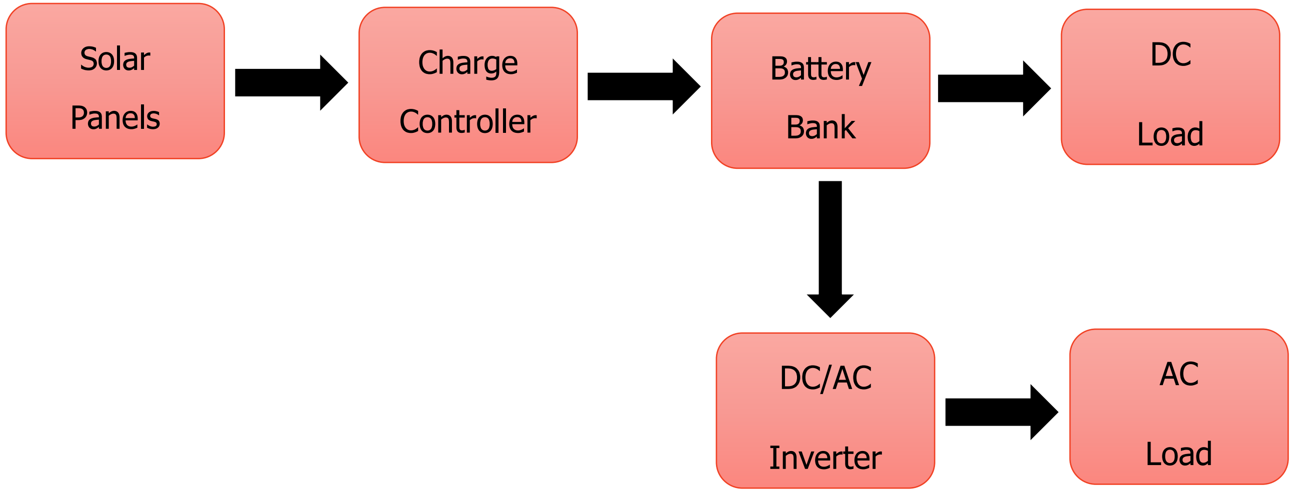
Electricity Generation

Different Sources

- Photovoltaic system using solar panels.
- Wind turbine.
- Geothermal Source.
- Micro hydro system.
- Diesel or biofuel generator.
- Thermoelectric generator.

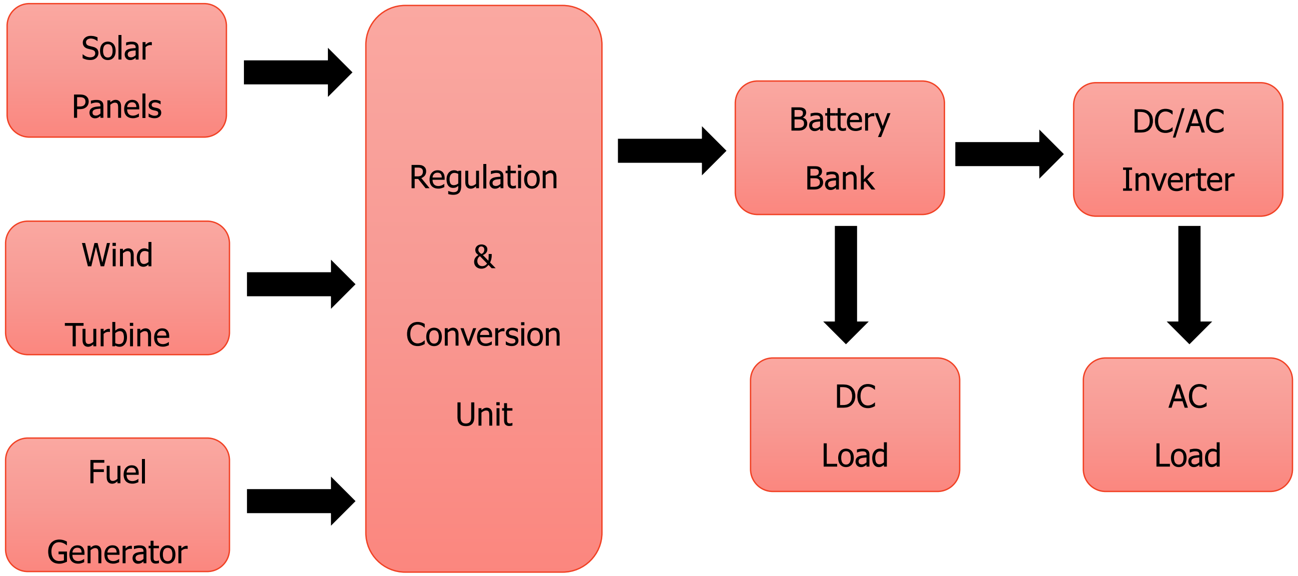
Electricity Generation

- These sources are used in the different countries depending on the abundance of it in each country.
- In the sunny countries most of the time, the solar source of electricity is preferable.
- On the other hand, in the countries that have rivers and seas or adjacent to oceans, it is best to use hydro source.



Hybrid Power System

- The hybrid power system is the power system that use more than one power system of renewable energy systems.
- The hybrid system may use two, three or more renewable energy sources.
- The criteria of choosing the accredited sources of the hybrid system depending upon the abundance of the source in the desired area. If the hybrid system use more than one abundant source, it becomes more reliable to serve the desired area in high efficiency and it ensures the service sustainability.



Solar Panels

Wind Turbine

Fuel Generator

Regulation & Conversion Unit

Battery Bank

DC/AC Inverter

DC Load

AC Load

Advantages of Off-grid System

Compared with Utility Grid Extension

- It is more cheaper than using the public utility grid.
- It is adaptable to local needs and conditions in contrast of the public utility grid.
- It could be operated by local technicians which leads to local employment.
- It is easier to be implemented than the installation of transmission lines of the public utility grid.
- It takes less time to be implemented which reduce the waiting time for the population to use it.
- It can use the local renewable energy sources to provide electricity.
- It is more reliable and there is no sudden interruptions in the electrical current.
- There is no bills or running costs.
- It has full local control.

Load Related Problems

Problems with Stand-alone System

- The wrong selection of loads that cannot be used with stand-alone systems.
- Low quality wiring and protection devices may affect the response of the system.
- Low efficiency loads may increase the power consumption.
- The stand-y mode in certain loads may consume power.
- High start-up currents for certain loads may overload the system.
- The difference between the circulating current and the consumed current in the case of inductive or capacitive loads.
- Harmonic distortion for the inverter waveform due to non-linear loads.
- The efficiency reduction due to mismatching between the inverter and the load.

Solar Home System

stand-alone photovoltaic system

- Solar home system (SHS) is a stand-alone photovoltaic system.
- Each solar system is unique and should be designed to achieve the user needs taking into account the geographic location.
- Each system should be designed to reflect the user energy consumption.
- SHS is cheap and effective supplier of power for lighting and home appliances.
- It may be used in rural areas to supply households by electricity for all human needs.
- Stand-alone solar power system is completely independent from any electric utility grid.

Solar Home System

stand-alone photovoltaic system

- Recently, hundreds of thousands of households were provided with electricity via SHS in faraway locations.
- SHS provides usually 12V DC which could be connected directly to DC appliances.
- Through using inverters, SHS can provide the households with effective AC electricity for the normal household's appliances.
- Solar energy system is more reliable source because it does not involve moving parts.
- Typically, SHS includes the following modules and components beside others:

  - One or more photovoltaic (PV) modules, each of them consists of solar cells.
  - Charge controller to distribute power and protect the batteries and appliances from damage.
  - One or more battery to store energy for use in night and rainy or cloudy days.

Standard of Living Improvement using SHS

SHS Contributions

- Improving population health by reducing indoor air pollution resulted from using kerosene lamps.
- Providing lighting and for home study.
- Providing lighting for home work.
- Giving the possibility to access to information and communication.
- Avoiding greenhouse gas emission by reducing the use of conventional energy resources.
- Providing cooling for medicines.

Technical Standards for SHS

- Solar home system has many technical standards to ensure functionality, reliability and safety.
- Some of these technical standards will be mentioned in the following sub sub-sections depending on the different parts that the SHS contains.

Module Installation of SHS Photovoltaic

Solar Home System Quality

- Identical modules should be used if more than one is required, and all should be connected in parallel.
- The modules must be ensure waterproof sealing for the solar cells.
- The mounting structure must hold the photovoltaic modules properly.
- The photovoltaic array and its support structure must be able to withstand wind gusts up to 160 km/hour without damage.
- The structure must be mounted at affixed angle with orientation that maximize the provided energy that will be supplied to the user over the year.
- All external connections in the structure must be corrosion resistant.
- The modules can be roof-mounted or ground-mounted. In both cases, extensive care must be taken to install the modules in a solid and robust way.

Circuit Protection and Charge Controls

- There are many criteria to protect users and system components.
- Also, the criteria must ensure the sustainability of the electrification providing service.

Circuit Protection and Charge Controls

Protecting Criteria

- preventing battery overcharge.
- preventing battery undercharge and excessive discharge.
- Circuit protection against short circuit of any load.
- Circuit protection against internal shorts in charge controller, inverter or other devices.
- Circuit protection against damage by the high photovoltaic open circuit voltage when it is connected to the controller without battery.
- Preventing night time discharge of the battery due to reverse current through the module.
- The charge controller must protect the system against high voltage and low voltage by automatic circuit disconnection.

Batteries

- Batteries are responsible about storing energy generated by the photovoltaic and use it to supply the loads when required.
- There are technical specifications that must be taken into consideration when designing the SHS system

Batteries

Energy Storage

- The useful life of the selected batteries must be five years or more.
- The electrical size of each battery must exceed 50Ah at 10 hours.
- The batteries must be supplied in a dry-charged condition and all chemicals and electrolyte must be supplied in accordance with battery supplier specifications.
- The batteries must be kept in properly designed protective enclosures.
- The batteries must have good charging efficiency.
- The batteries must have low-self discharge.
- The batteries must have low charging currents.

- In this chapter, the off-grid, stand-alone, mini-grid and hybrid electrical system were discussed. Technical specifications and quality criteria were mentioned. The difference between off-grid and stand-alone was discussed. Solar home system and its advantages were discussed. Several renewable energy systems were mentioned.

Summary

Off-grid and Stand-alone Energy Systems

Thank You

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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Integrating of Renewable into energy electrical grid

Lecture 13: Challenges, Solutions, and Grid Codes

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This week's topics…

- RE integration challenges
- Adopted solutions for RE Integration
- Grid Code

Section Outline

While electrical power grids have been designed to deal with predictable generation and variable load patterns, the increasing number of renewable energy projects can pose new challenges for utilities and system operators because of its uncontrollable nature uncertainty.

Section 1

RE Integration Challenges

Aim of Renewable energy integration

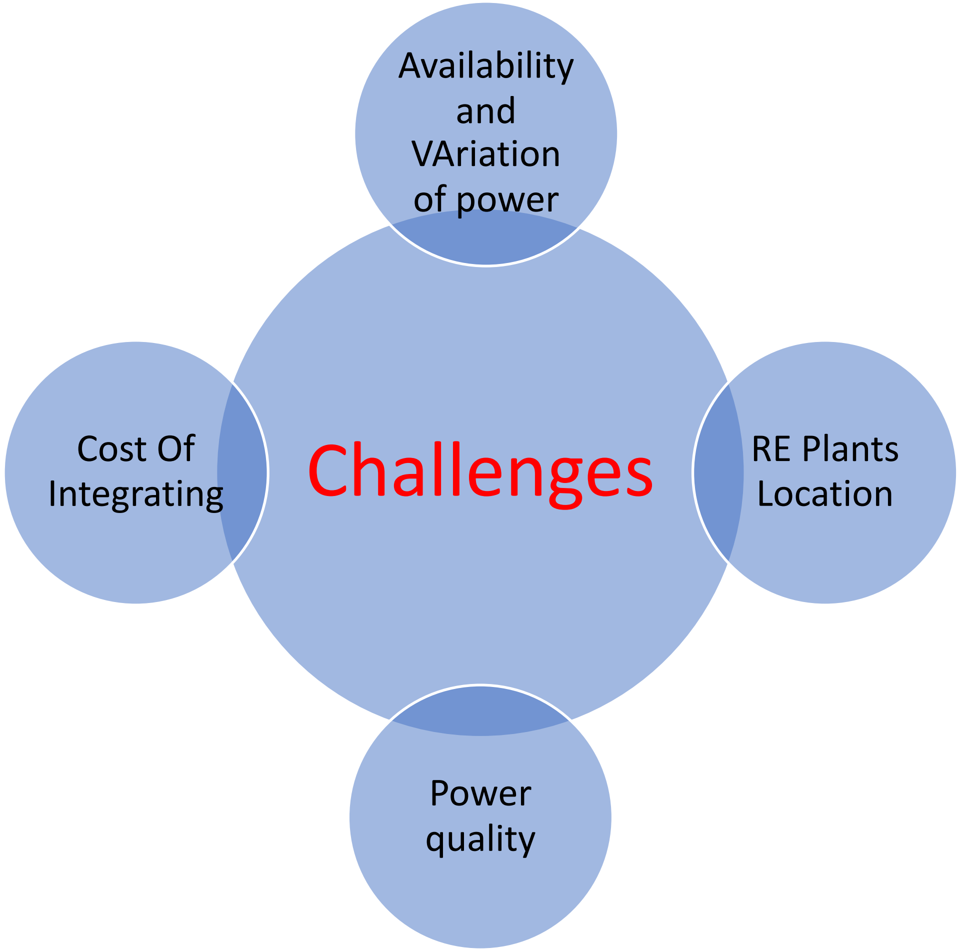
○ The integrated RE is the process of incorporating renewable energy into the existing electric distribution and transmission grids. The AC grid could have distributed generation, renewable energy plants, energy storage, thermally activated technologies. The aim of Renewable energy integration is to help utilities to:

1. Lower carbon emissions through increased share of renewable energy and other clean technologies.

Aim of Renewable energy integration- cont.

2. Better asset management through coordination between distributed generation and customer loads which leads to peak load leveling and avoid peak-time tariff.
3. Enhance reliability, security, and resiliency in highly constrained areas of the electric grid
4. Support cut in fossil fuel use by enabling plug-in electric vehicle (PHEV) operations with the grid.

RE Integration Challenges



Challenges

Availability and VAriation of power

RE Plants Location

Power quality

Cost Of Integrating

13.2.1 Availability and Variation of Power generation

- One of the major challenges in RE-Grid integration is the power generation comes from RE rely on natural resources that cannot be controlled.
- In PV-solar energy delivering power stand up on when daylight is accessible and off around evening time.
- Wind vitality relies upon the accessibility of wind, so if the speed of wind is zero or exceptionally low, the turbine won't turn, and this outcome in zero power flow to the grid.
- This uncertainty of wind and solar generation can present difficulties for network administrators. Variability in generation sources can require additional actions to balance the system. Greater flexibility in the system may be needed to accommodate supply-side variability and the relationship to generation levels and loads.

13.2.2 Location of RE Plants

- Most of RE plants that share their energy with the grid are large scale of capacity, so usually the area of such one plant is considerable.
- Sometimes, we are forced of the RE sources locations due to several factors that each technology has own reasons of choosing the location.
- Picking a place to operate one of RE technology involves on many elements that make RE-Grid integration under challenges:
    1. Some RE source are not available in each region.
    2. Distance between RE source and the grid is a major aspect in term of cost and efficiency.
    3. RE sources depend on weather, climate, and geographical location. For example, solar energy in sunny locations is more efficient than foggy or cold locations due to the high percent of sun radiation time per day in these locations. As a result, the integration will be more flexible in these locations.

Grid structure and Types of power generators

The AC grid could have different types of input of power generation: conventional/ unconventional power plants and RE plants “wind, solar, etc.”

The output of power from RE must be an AC power in order to meet integration conditions where allow power to transfer to the substation, which might be a distribution substation.

13.2.3 Cost of integration

- The adequate assessment of renewable energy integration costs is vital for policy making and system planning.
- Any fiscal assessment of the transition towards renewables-based power systems should, therefore, take into account all different cost components for this integration, these costs should be carefully interpreted and not so much credited to RE, especially when the system is adaptable enough to manage fluctuation.
- The extra cost of renewable integration into the existing power grid can be classified into **grid infrastructure** and **operation costs**.

A. Grid infrastructure costs

Grid connection costs

- Include the cost of having a new cable from the new RE plant to the existing grid. This cost are proportional to the distance between the new plant and the grid, the voltage level of the connection line.
- This cost are related to the isolation type, and the availability of standard tools.
- The grid connection cost has significant economic for renewables projects located in remote areas. Based on many case studies and current practice, grid connection costs for vast majority of renewable projects in highly populated regions are estimated to be between 0% and 5% of the total project investment cost.
- In general, the grid connection cost is the dominant financial part in wind projects infrastructure costs. In most projects, grid connection costs are considered by the investor as part of the initial investment cost.

A. Grid infrastructure costs

Grid upgrading costs

- cover the cost of new network equipment needed to integrate renewable project into the current grids.
- These costs are highly related to the capacity of the renewable energy project, Renewable power plants location, and the structure of the current grid.
- Based on load flow analyses, many studies carried out in different countries suggest a strong correlation between the cost of grid upgrading and the level of renewable electricity share, i.e. costs in the range between EUR 0.5–3/MWh for 20%–30% renewable share in annual electricity generation.

B. System operation costs

- System operation costs cover the extra costs related to the conventional part of the power system caused by the integration of renewable projects. It can be divided into:

B. System operation costs

Profile costs

- include all three impacts of the temporal mismatch between RE generation and load profile:
  - capacity costs
  - reduced average utilization of thermal power plants
  - Curtailed RE generation when power supply exceeds demand.
- The capital cost due to the utilization effect is the single most important integration cost component and can amount to more than half of the integration costs at 30%-40% penetration share (EUR 15–25/MWh).
- At low penetration rates, the profile costs are estimated to be zero or can result in savings.

B. System operation costs

Short-term system balancing costs

- In order to maintain a secure and stable grid operation, demand and supply (generation) must be continuously balanced.
- Due to the variability and uncertainty properties of VRE generators, the reserve capacity needed for up-and down–regulation increases if compared to the case where the same energy is delivered by conventional power.
- In particular, the impact of second-to-minute scale wind and solar PV power variability is modest or negligible while minute-to-hour scale variability may affect grid operation more significantly.
- The increased requirements for reserve power correspond to the extra costs for the conventional part of the power system. These extra costs originate from the measures taken to ascertain increased reserve power caused.

13.2.4 Power Quality

Definition

- Power quality means "the concept powering and grounding sensitive electronic equipment in a manner suitable for the equipment"[IEEE1100]
- The power quality definition according to IEEE is “The measure, analysis and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency”

Power Quality Indices

13.2.4.1 Flicker

- Visual variation of input voltage in the specific duration, the flicker may be expressed as the change in voltage over nominal expressed as a percent.
- For example if the voltage at a 220 V and the voltage increase to 225 V and drops to 217 V the flicker

$$(f) = \frac{225-217}{220} = 3.3636\%. \qquad \text{Equation 13-1}$$

- Or impression of unsteadiness of visual sensation induced by a light stimulus whose spectral or luminance distribution fluctuates with time or the flicker is the repaid change in fluctuating loads which result in visual sensation as induced by a light stimulus whose spectral or luminance distribution fluctuates with time the IEC standard provides total flicker levels for HV system must not exceed certain value as mention in standard NEPCO transmission grid code.
- In flicker definitions there are two concepts the first one short term flicker for 10 minutes (Pst) the last one long term flicker (Plt) .

Flicker Cont.

- $(\mathrm{Plt}) = \sqrt[3]{\frac{\sum_{i=1}^{n} \mathrm{Pst}^3}{N}}$ Equation 13-2

○

○ The purpose of case study is to insure that the Jordan wind farm is compliant with standards and grid code and to do this study the following equation and coefficient equations are used

- $\mathrm{Pst}\Sigma = \mathrm{Plt}\Sigma = \frac{1}{S_k} \times \sqrt{\sum_{i=1}^{N} (ci(\psi_k, v_a) \times S_{n,i})^2}$ Equation 13-3
- $c_i(\psi_k, v_a) = p_{st} \frac{s_k}{s_n}$ Equation 13-4

○ Where $c_i(\psi_k, v_a)$ is a flicker coefficient of the wind turbine for the given network impedance per phase ψ_k and for given annual average wind speed v_a at hub height of the wind turbine at the site, s_n is the related apparent power of the wind turbine and s_k is short circuit apparent power

Power Quality Indices

13.2.4.2 Power Frequency:

- Power frequency is the nominal frequency of the oscillation of Alternating Current (AC) in an electric power grid transmitted from power generation station to the end –user and the frequency in the range used for alternating currents supplying power (commonly 50 or 60 Hz or cycles per second).

Power Quality Indices

13.2.4.2 Power Frequency:

Under normal operation and introconnected with other systems	**49.95Hz to 50.05 Hz**
Under normal operation but not interconnected with other systems	49.95Hz to 50.05Hz
Under system stress	48.75Hz to 51.25Hz
Under extreme system fauult conditions all generating units should have disconnected by these (high or low) frequencies unless agreed otherwise in writing with the TSO	By a frequency greater than or equal to 51.5Hz By a frequency less than or equal to 47.5Hz

Table 13-3 frequency variation

Power Quality Indices

13.2.4.3 Crest Factor

- Is defined as the ratio of instantaneous peak value to Root Mean Square (R.M.S) value of voltage or current waveform it is a numerical value without any units, the Crest Factor for normal sinusoidal wave is 1.414.
-
  - $\mathrm{CF}=\frac{peak\ amplitude}{root\ mean\ square}$ Equation 13-5

Power Quality Indices

13.2.4.4 Voltage Unbalance (imbalance)

○ Is defined the ratio of the negative (V_n) or zero(V_z) sequence component to the positive sequence component, the negative and zero sequence voltage in power system result from unbalance loads.

- Voltage unbalance = $\frac{\text{max deviation from average voltage}}{average\ voltage}$ Equation 13-6
- $max\ deviation\ from\ average\ voltage = max\ value - average\ value$

○ Or Voltage variation in a three-phase system in which the three voltage magnitudes or the phase-angle differences between them are not equal.

Causes of Voltage unbalance

Large single-phase loads (induction furnaces, traction loads).

Incorrect distribution of loads by the three phases of the system.

Voltage Unbalance cont.

Table 13-4 Voltage unbalance standard and threshold values

No.	Standard	Maximum value
1	ANSI (American National Standards Institute	3.0%
2	NEMA(national equipment manufacturers association)	1%
3	NEPCO(national electrical power company) transmission Grid Code	1% under

Power Quality Indices

13.2.5.1 Voltage Sag

- Is an event causes RMS reduction in AC voltage at power frequency in short period (few seconds) like heavy loads such as motor or arc furnaces.
- Voltage Sag is defined as a short reduction in voltage magnitude for duration of time and is the most important and commonly occurring power quality issue.
- The definitions to characterize voltage sag in terms of duration and magnitude vary according to the authority. According to the IEEE defined standard (IEEE Std. 1159, 1995), voltage sag is defined as a decrease of rms voltage from 0.1 to 0.9 per unit (pu), for a duration of 0.5 cycle to 1 minute.

Voltage Sag

Sag Causes:

Faults on the transmission, distribution network or consumer.

Connection of heavy loads and start-up of large motors.

Power Quality Indices

13.2.5.2 Voltage Swell

- RMS increase in AC voltage at power frequency in short period (few seconds).
- Rapidly increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds.

Voltage Swell

Causes:

Start/stop of heavy loads.

Poorly dimensioned power sources.

Poorly regulated transformers.

Power Quality Indices

13.2.5.3 POWER SYSTEM HARMONICS

Harmonics Definitions:

- Sinusoidal component of a periodic wave having frequency that is an integral multiple of the fundamental frequency.

POWER SYSTEM HARMONICS

- In the generation system is normally produced constant voltage and frequency 50 or 60Hz depend on the country around the world ,when a source of sinusoidal voltage is applied to a nonlinear devices like the power electronics and switching devises or loads ,the resulting current is not perfectly sinusoidal .in the presence of system impedance this current causes a non –sinusoidal voltage drop then produce voltage distortion at the load terminal.
- Harmonics are not only produced by wind power units but also loads that draw a nonlinear current like a transformer operated at higher flux density during an overvoltage will operate in the saturation region producing current a non-sinusoidal waveform and not only produce odd harmonics but also produced even harmonic and theses harmonic not be taken in consideration in the steady sate , and in fact all electrical equipment that contains power electronics produces harmonics and converter is similar .

POWER SYSTEM HARMONICS

general harmonic expressions and indices

- There are many indices to expression for harmonics distortions, the common one is total harmonic distortion (THD), which is defined as the root mean square (R.M.S) of the harmonics expressed as a percentage of the fundamental component
-
- $THD_V = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1}$ for voltage Equation 13-7
- $THD_i = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1}$ for current Equation 13-8
- For most application it is sufficient to measure harmonic from 2nd to 25th but the most common standard specify up to 50th

general harmonic expressions and indices cont

- For current distortion as above mention in equation number 3.3 can be also calculate by THD but can be misleading when the fundamental load current is low and when the load is light a high THD value for input current not be significant concern .so to avoid ambiguity and mismatch a total demand distortion factor is used and defined as:
- $TDD = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_R}$ Equation 13-9
- Where: I_R is rated load current magnitude.

13.3 Solutions

- A variety of solutions are available to mitigate integration challenges. Key factors in selecting methods are the cost-effectiveness of the method and the nature of the current grid.
- Generally, grids need additional flexibility to be able to accommodate the extra variability of renewables. Flexibility can be in the form institutional changes, operational practices, storage, demand-side flexibility, flexible generators, and other mechanisms.
- Several of these mechanisms are discussed below.

Solutions

13.3.1 Advanced Forecasting

- Advance forecasting for Wind and solar power can mitigate the uncertainty of intermittent renewable generation.
- Advance forecasting can help grid operators more efficiently plan for generating units dispatch to adapt with the changes in wind and solar generation and to be ready for any for extreme events.
- Forecasting can lead to reduction in the amount of operating reserves needed for the system and costs of balancing the system. Short-term forecasting can range from one hour ahead to one week ahead.
- One hour ahead forecast errors typically range from 3% to 6% of rated capacity and a day ahead forecast error range from 6% to 8% on a regional basis. In comparison, load forecasting errors typically range from 1% to 3% day-ahead.

Solutions

13.3.2 Fast Dispatch and Larger Balancing Authority Areas

- Quick dispatch mitigates the intermittent nature of renewable generation because it reduces the need for regulating resources, improves efficiency, and gives access to a more extensive arrangement of assets to balance the system.
- When using fast dispatch techniques, generation can track load level more precisely, which will reduce the need for more costly regulating reserves. This enables extra environment friendly balancing and utilization of the most economical resources within the system.
- Five-minute dispatch is currently the norm in ISOs throughout the country, serving over 2/3 of the national load.

Solutions

13.3.3 Reserves Management

- Reserve management practices can be modified to assist address the variability of wind and photo voltaic power.
- Practices that decrease average reserve requirements can lead to widespread value savings. Potential tools for managing variability consist of putting limits on wind electricity ramps to reduce the need for reserves and allow variable renewables to grant reserves or different ancillary services.

Reserves Management cont.

- Limiting up ramps is any other workable tool for managing variability. Because reserve stages are set to address incredibly low-probability, large changes in wind output, modest limits on wind era can substantially reduce the need for balancing reserves, yielding value savings.
- Ramp events that affect plants across a balancing authority vicinity result from large-scale weather activities that can be extra without difficulty predicted than nearby climate events. By imposing ramping limits on windmills when large-scale climate events are forecasted, balancing reserve requirements may also be drastically reduced

Solutions

13.3.4 Demand Side Management

- Demand-side management can also contribute to the integration of variable renewable generation, especially in cases of fast ramps or extreme events.
- Supply reserves and ancillary services as well as peak reduction can be results of demand response.
- The use of demand side management to balance the system at some stage in infrequent occasions in which there is tremendous under or oversupply of renewable generation can lead to value financial savings in contrast to always keeping extra reserves.

Solutions

13.3.5 Energy Storage

- Advances in energy storage technologies ought to notably alternate how variability and uncertainty are managed by way of the grid.
- The energy storage market has been increased dramatically in the last few years. As energy storage becomes more cost-effective and more players entered the market.
- Energy storage will become more widely affordable within the coming few years. Energy storage will facilitate renewable integration and provides the grid with needed flexibility by shifting load and generation peaks. It also can help to maintain grid reliability and stability

Energy Storage Cont.

- Although strength storage is not quintessential to integrate renewable energy, lower priced storage may want to minimize integration challenges, as contries try to meet excessive renewable power targets.
- New battery applied sciences ought to appreciably enlarge the price of wind, which frequently produces electricity at some stage in the evening when demand is low.
- In areas where solar manufacturing may also peak a few hours earlier than demand is highest, energy storage ought to enable photo voltaic electricity to be used in the course of times of peak demand when electrical energy is most highly-priced.

13.4 Renewable Resources Grid Code

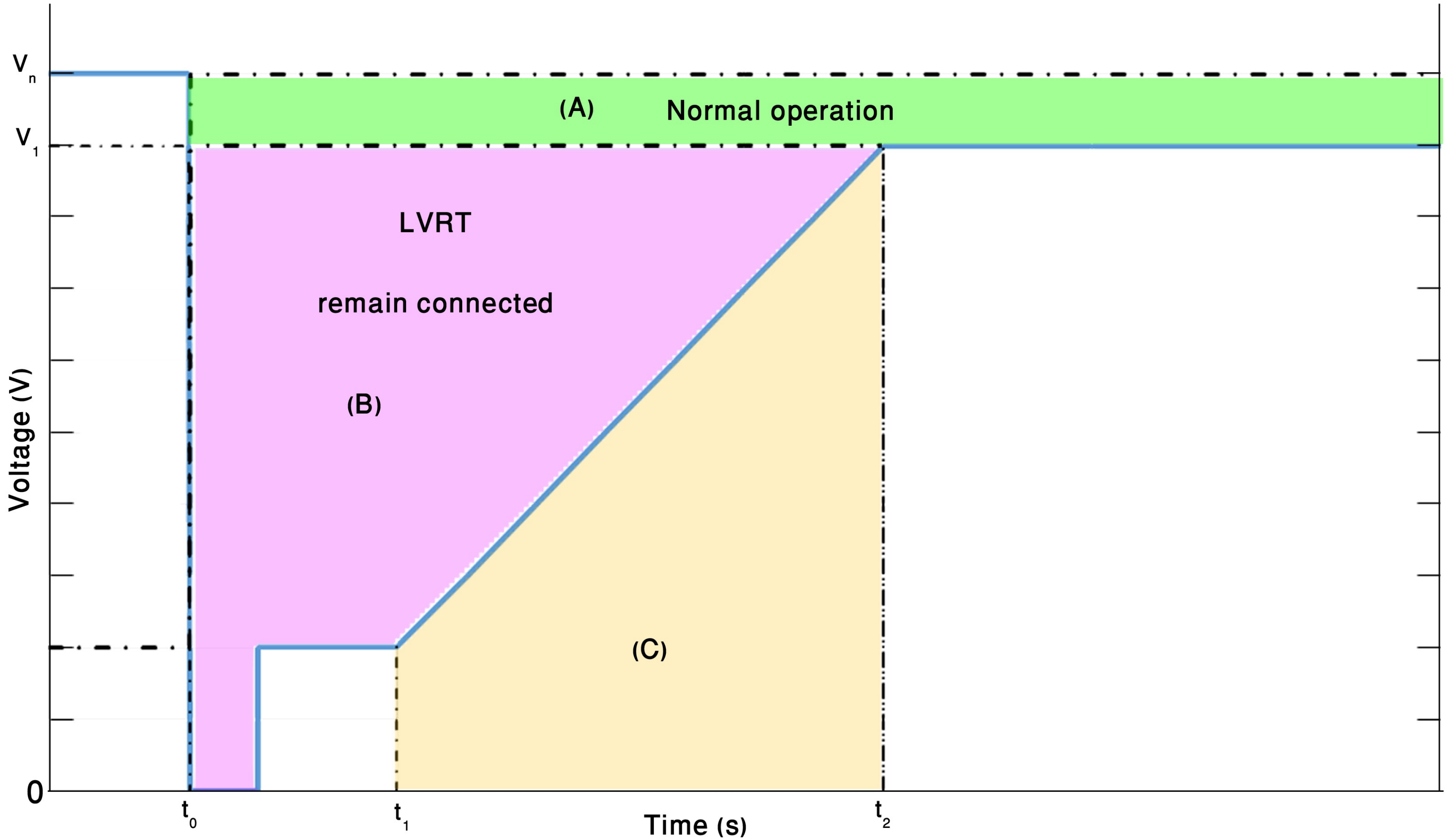
- All Generators connecting to the electrical grid must comply with the grid Code governing the electric network.
- The grid Code was originally covering conventional synchronous generators.
- With the increase number of Intermittent (wind and solar photovoltaic) Renewable Resources this code was revised to contain these types of resources. The following set comprises of common grid codes technical connection requirements.

Renewable Resources Grid Code

13.4.1 LVRT requirements

- Low Voltage Ride Through (LVRT) capability considers one of the most important requirements in modern grid codes, which means that the renewable energy conversion system must withstand grid voltage dip (during grid faults) to a certain percentage of the nominal voltage for a specific duration and operate normally.
- After clearance of fault, renewable energy must restore active and reactive power fast enough to the prefault value. In some countries, the renewable system is required to supply reactive power during the fault and operate like conventional synchronous generators to help maintain voltage stability.

LVRT requirements cont.



curve limits for low-voltage ride-through requirements

Renewable Resources Grid Code

13.4.2 HVRT requirements

- Similar to the grid code for LVRT requirements, some modern Grid codes insist that renewable plants should stay connected to the system when the voltage swell (overvoltage) take place for a specific time.

- This is the so-called HVRT capability requirements, which aims to maintain the overall stability of grid voltage and avoid catastrophic situations induced by overvoltage.

HVRT requirements Cont

- When the grid voltage swell occurs, causing overvoltage problems, modern GCs now require the HVRT functionality to be applied, in spite of the fact that voltage swell grid fault is less common and occurs hardly ever when compared with voltage sag.
- The HVRT requirements depending on specific characteristics (RE penetration level and operational methodology) of each power system differ from each other.

Renewable Resources Grid Code

13.4.3 Reactive power requirements

- To ensure grid voltage stability which is proportional to the reactive power.
- Consequently, to prevent the instability of utility grid because of high penetration of renewable enrgy, modern Grid codes require renewable energy generators to contribute in grid stability by providing reactive support during and after disturbances, similar to traditional power plants.
- Reactive support can be in form of reactive power control (static grid support) and reactive current injection (dynamic voltage support).

Renewable Resources Grid Code

13.4.4 Voltage and frequency range

- Modern Grid codes require large-scale renewable energy plants to continuously maintain the voltage and frequency within operational variation limits during steady-state operation of the power system.
- The system operator has to keep the voltage and frequency stable within acceptable ranges under variable operating situations.
- Therefore, the Grid codes define the electrical limits under which the renewable plant must operate continuously.

Voltage and frequency range Cont.

- Many countries such as Germany, Japan, South Africa, Italy, and China adopt a grid code for voltage variety at PCC by ±10% (90%-110%) of the nominal voltage.
- The extent areas of frequency operation in international GCs have the same range between 47 and 52.0 to 53.0 Hz.

Thank You

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