ENE 101:
Introduction to Energy Engineering

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Week 7: Energy conversion:

Wind Energy

Wind energy conversion machines have evolved over the past 2000 years, mostly by **trial and error**. Although there are many different configurations of wind machines, most of them can be classified as either horizontal-axis wind turbines (**HAWTs**), which utilize rotors that rotate about a horizontal axis parallel to the wind, or vertical-axis wind turbines (**VAWTs)**, which have rotors that rotate about a vertical axis.

HAWTs have all of their drivetrain equipment located on a **tower,** which makes servicing somewhat difficult, their blades are subjected to **cyclic stresses** due to gravity as they rotate, and they **must be oriented with respect to the wind**. However, they may be placed on tall towers to access the **stronger winds** typically found **at greater heights**. VAWTs, on the other hand, have most of their drivetrain on **the ground**, **do not experience cyclic gravitational stresses**, and **do not require orientation with the wind**. VAWTs, however, cannot be placed on tall towers to exploit the stronger winds at greater height, and their blades are subject to **severe alternating aerodynamic loading** due to rotation.

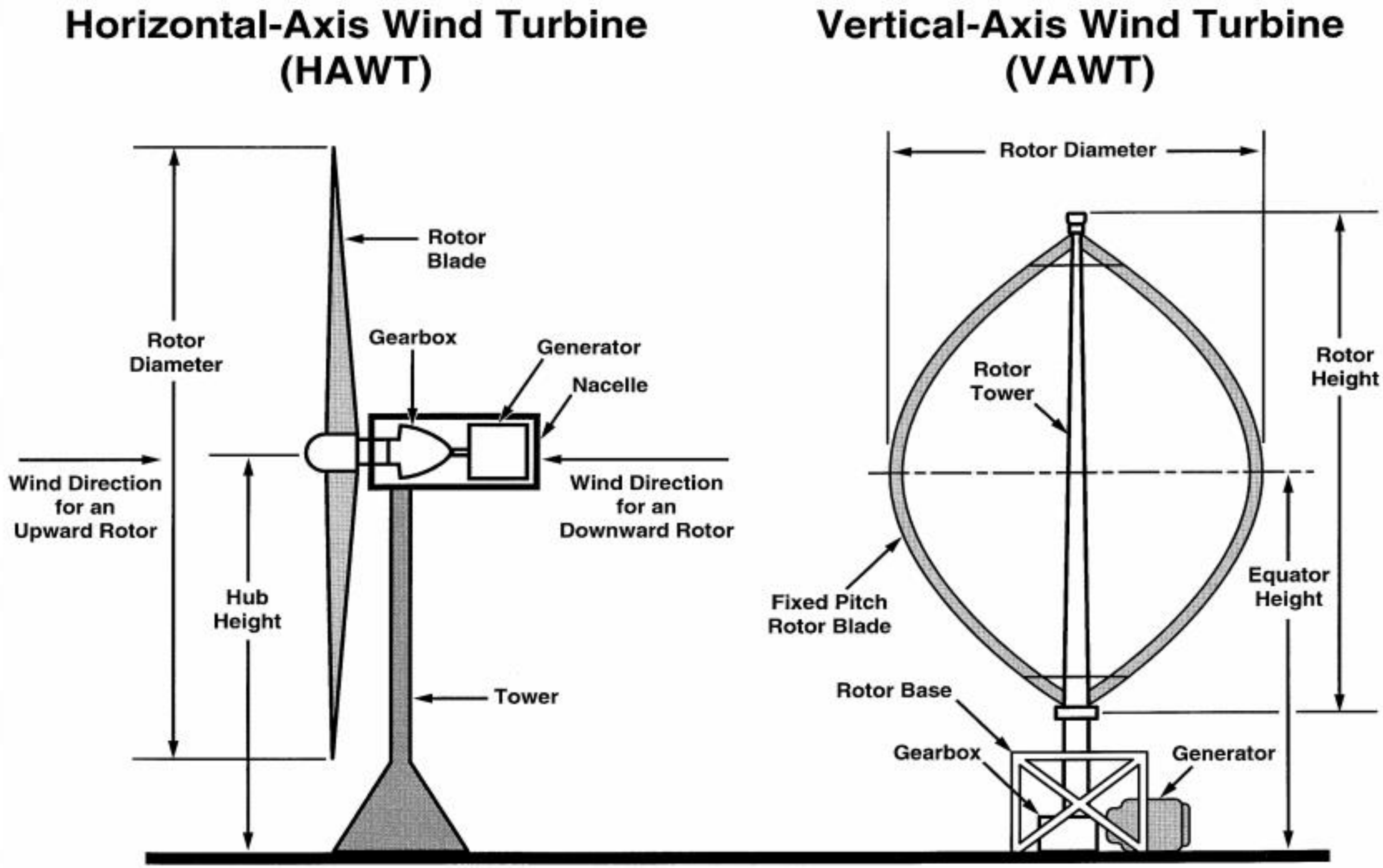


FIGURE 8.11.1 Wind turbine configurations.

FIGURE 8.11.2 Wind farm both horizontal-axis and vertical-axis turbines.

Wind Turbine Aerodynamics

Items exposed to the wind are subjected to **both drag** (in the direction of the wind) and **lift** (perpendicular to the wind) forces. The **earliest wind machines used drag** to produce power. Modern wind turbines rely on **airfoil-shaped blades** that generate large amounts of lift to produce power more efficiently than the drag machines. Let us consider how efficient these machines are at extracting energy from the wind.

Figure 8.11.3 illustrates the flow field about a translating **drag device**. The drag results from the relative velocity between the wind and the device, and the power that is generated by the device (the product of the drag force and the translation velocity) is given by

$$\mathrm{P} = Dlv = [0.5\rho(\mathrm{U}-\mathrm{v})^2]C_D\,\mathrm{clv}$$

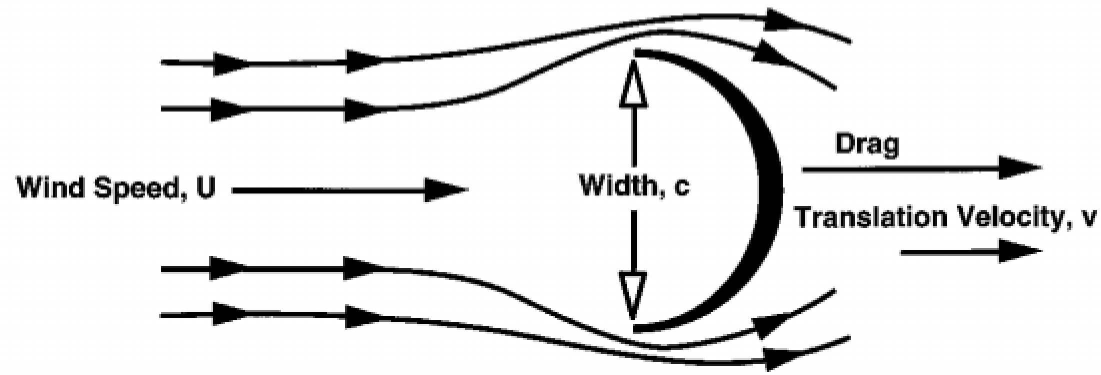


FIGURE 8.11.3 Schematic of translating drag device.

where

P = power extracted in watts
D = drag force per unit spanwise length in n/m
l = length of device (distance into the page) in m
v = translation velocity in m/sec
ρ = air density in kg/m^3
U = steady free-stream wind velocity in m/sec
C_D = drag coefficient; function of device geometry function
c = width of device (perpendicular to wind) in m

The velocity of the device must always be less than the wind velocity, or no drag is generated. The **power coefficient** (the ratio of the power extracted to the power available in the area occupied by the device) for this machine is

$$C_p = \frac{P}{0.5\rho U^3 cl} = \frac{v}{U}\left[1 - \frac{v}{U}\right]^2 C_D$$

Now consider a device that utilizes lift to extract power from the wind. Figure 8.11.4 illustrates an airfoil that is translating at right angles to the wind direction and is subject to both lift and drag forces. The relative velocity across this surface is the vector sum of the free-stream wind velocity and the wind speed induced by translation. The angle between the direction of the relative velocity and the chord line of the airfoil is termed the angle of attack α. In this case, the power is given by

$$P = 0.5\rho U^3 cl \frac{v}{U}\left[C_L - C_D \frac{v}{U}\right]\sqrt{1 + \left(\frac{v}{U}\right)^2}$$

where c = airfoil chord length in m and C_L, C_D = lift and drag coefficients, respectively; functions of airfoil shape and α. The power coefficient then is

Figure 8.11.5 compares Equations (8.11.2) and (8.11.4) using $C_L = 1.0$ and $C_D = 0.10$ for the airfoil (easily achieved with modern airfoils) and a maximum drag coefficient of 2.0 for the drag machine. The airfoil has a maximum power coefficient of 15, compared with 0.3 for the drag device, or 50 times more power per unit of projected area. Moreover, operating a lifting device at velocities well in excess of the wind velocity is easily achieved with rotating machines.

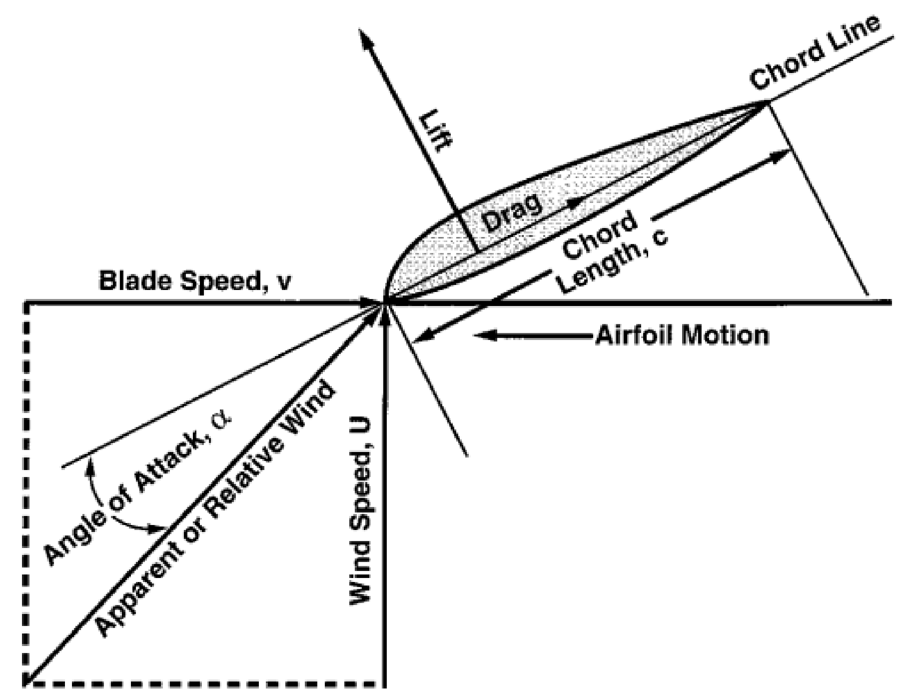


FIGURE 8.11.4 Schematic of translating lift device.

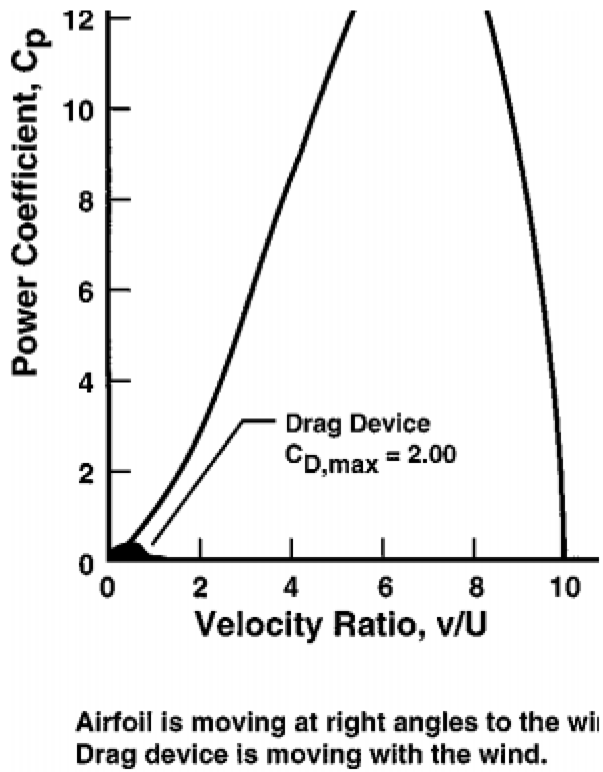


FIGURE 8.11.5 Comparison of power coefficients for a translating airfoil and a translating drag device. The airfoil is moving at right angles to the wind direction. The drag device is moving in the wind direction.

Machines utilize lift-producing blades to capture wind energy:

- Aerodynamic Models
- Momentum Models
- Vortex Models
- Local Circulation Method

Common Model Limitations: All of the **aerodynamic models** in use today use airfoil section characteristic tables (**lift and drag coefficients as functions of angle of attack and Reynolds number**) to determine the blade loading and turbine performance. Static two-dimensional wind tunnel test results or two-dimensional static airfoil design code predictions are modified with empirical, semiempirical, or analytic methods and used to estimate blade loads under three-dimensional, dynamic conditions. The greatest difficulty in obtaining accurate load predictions with any performance code is **the determination of the appropriate airfoil section characteristics.**

Momentum Models

The typical performance of various types of wind machines is compared with the Betz limit in Figure 8.11.6 where the variation of the turbine power coefficients with the **tip–speed ratio** (the ratio of the speed of the blade tip to the free-stream wind speed) are presented. Even though the maximum performance of modern HAWTs and VAWTs is well above that of the older machines, it still falls more than 10% below the Betz limit.

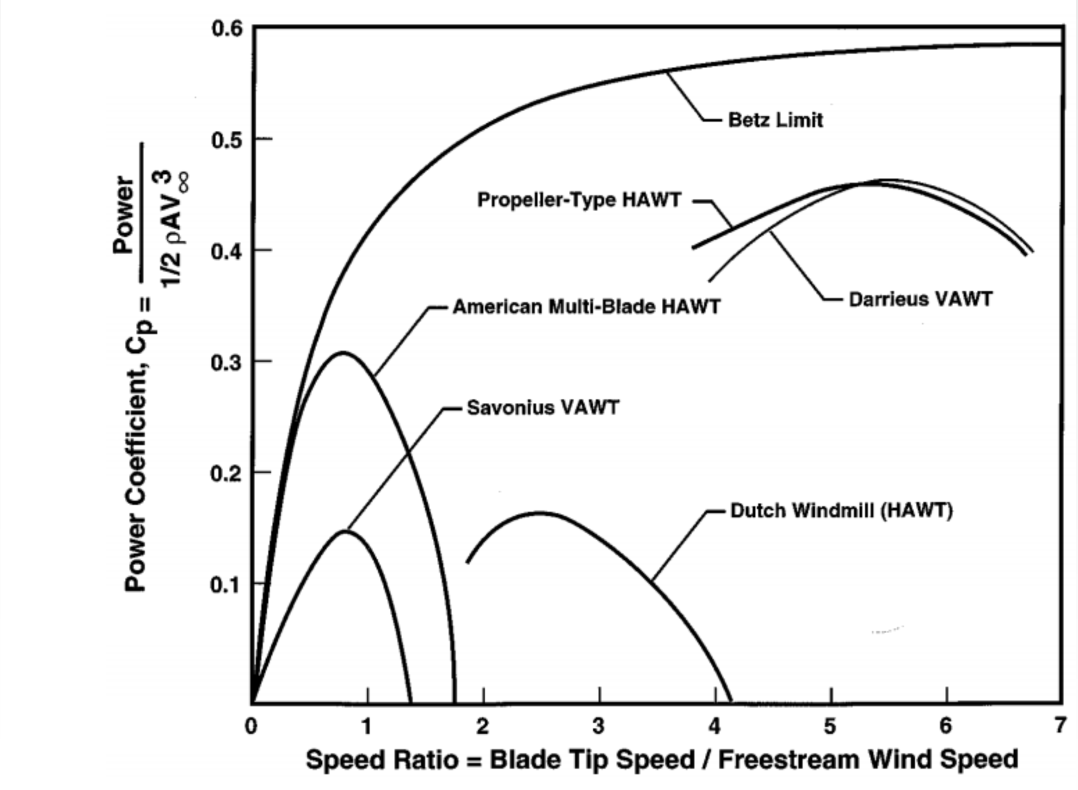


FIGURE 8.11.6 Typical performance of various types of wind turbines.

$$P = 2\rho A V^3 a(1-a)^2$$

$$a = (V - v)/V$$

$$C_p = 4a(1-a)^2$$

Wind Turbine Controls

- *Brakes:* Most turbines utilize mechanical brakes, frequently in conjunction with aerodynamic brakes, to stop the rotor and to keep it from rotating when the turbine is not generating electricity. Whatever type of braking system is used, it should be a fail-safe design that will automatically activate to slow or stop the rotor in the event of an electrical system failure.

- *Yaw Systems:* Virtually all upwind and a few downwind HAWT turbines incorporate an active yaw control system, using wind-direction sensors and electric or hydraulic drive motors, to orient the rotor with respect to the wind. VAWTs do not require yaw systems.

Wind Turbine Controls

- *Peak Power Regulation:* All turbines incorporate some method of limiting the peak power produced. This enables the generator to operate near its design power rating, where it is most efficient, over a range of wind speeds.

- *Controller:* Every wind turbine contains a controller, usually a microprocessor-based system, to control turbine operations. The basic turbine controller will start and stop the machine and connect or disconnect the generator output lines to the grid, as needed; control the operation of the brake system; control the operation of the yaw and pitch systems, if present; perform diagnostics to monitor the operation of the machine; and perform normal or emergency shutdown of the turbine as required.

Wind Power Calculation

- Power= work / time

  $= \text{Kinetic Energy} / t$

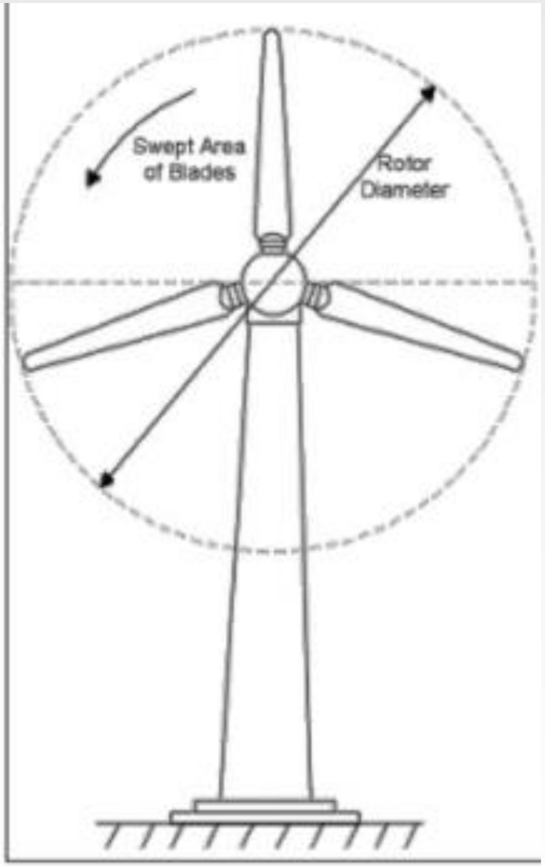
  $= \frac{1}{2} m V^2 / t$

  $= \frac{1}{2}(\rho A d) V^2 / t$

  $= \frac{1}{2} \rho A V^2 (d/t)$

  $= \frac{1}{2} \rho A V^3$

- Power in the Wind $= \frac{1}{2} \rho A V^3$

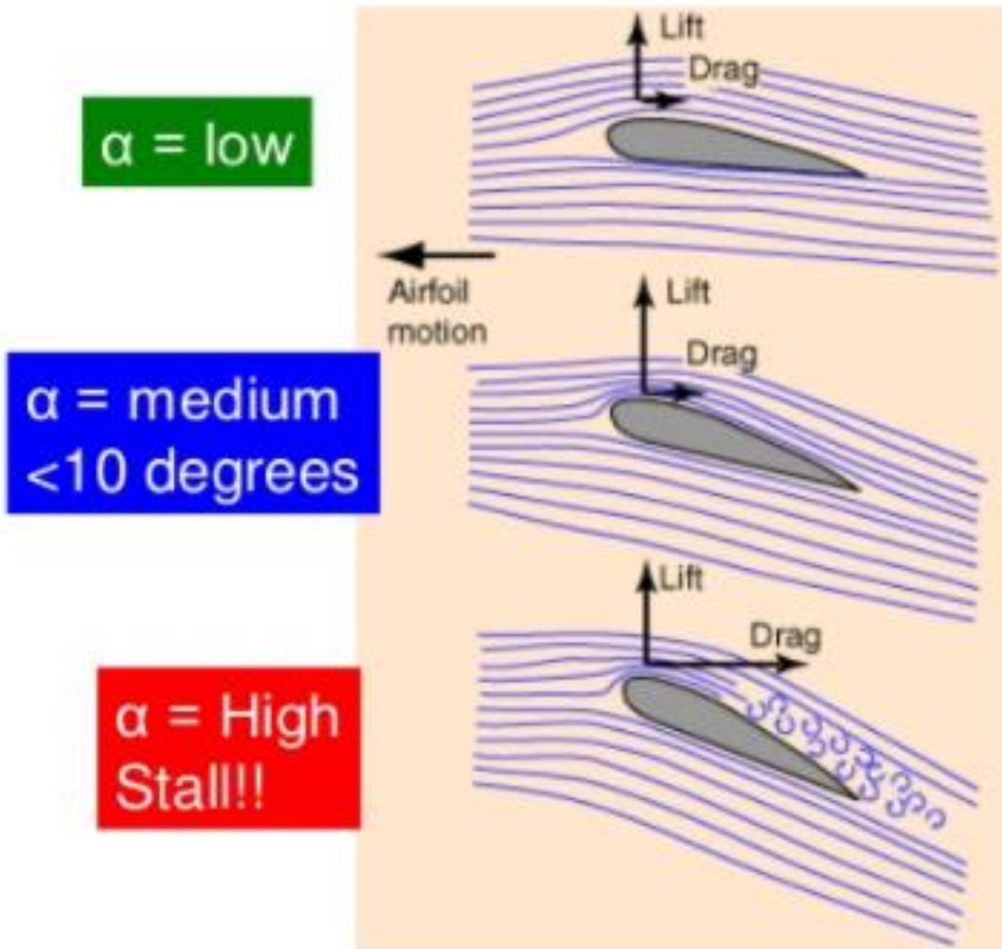


https://www.slideshare.net/Turbomach2010/wind-turbine-2554710

Lift and Drag Forces

- The *Lift Force* is perpendicular to the direction of motion. We want to make this force BIG.

- The *Drag Force* is parallel to the direction of motion. We want to make this force small.



Example on calculating wind turbine energy, wind energy and wind turbine efficiency:

Wind Energy

$$P_{in} = \frac{E}{t} = \frac{\frac{1}{2}mv^2}{t} = \frac{\frac{1}{2}\rho V v^2}{t} = \frac{1}{2}\rho A v^2\left(\frac{l}{t}\right) = \frac{1}{2}\rho A v^3 \quad (\rho = 1.29\frac{kg}{m^3})$$

$$P_{in} = \frac{1}{2}\left(1.29\frac{kg}{m^2}\right)(0.2\ m^2 \times 0.3\ m^2)\left(3\frac{m}{s^2}\right)^3 = 1.0449\ w$$

Wind Turbine Energy

$$P_{out} = F \cdot V$$

$$F = m \cdot g \quad (m = mass, g = 9.81\frac{m}{s^2})$$

$$V = \frac{\text{Conference}}{t} = 2\pi r f \quad (f = \frac{rotations}{sec})$$

$$P_{out} = 0.347\ kg \times 9.81\frac{m}{s^2} \times 2\pi \times 0.003175 \times 0.7 = 0.0475\ w$$

Efficiency

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} \times 100 = \frac{0.0475\ w}{1.0449\ w} \times 100 = 4.55\ \%$$

http://cfd2012.com/rotating-wind-turbine.html

Defining Terms

Betz limit: Maximum fraction of available wind energy that can be extracted by a wind turbine rotor, according to momentum theory.
Momentum theory: A method of estimating the performance of a turbine by equating the time rate of change of air stream momentum through the turbine to the force acting on turbine blades.
Power coefficient: The ratio of captured energy to the energy available in the reference area.
Resonance: A vibration of large amplitude caused by a relatively small excitation at or near a system natural frequency.
Stall: A condition in which an airfoil experiences a decrease in lift and a large increase in drag.
Tip-speed ratio: The ratio of the speed of the blade tip to the free-stream wind speed.
Wind-diesel system: An electrical-generation system that utilizes both diesel engine-powered generators and wind turbines to create a dependable, consistent power system.

Ocean Energy Technology

- The ocean contains a vast renewable energy potential **in its waves and tides**, in the **temperature difference** between cold, deep waters and warm surface waters, and in the **salinity differences at river mouths**. Waves offer a power source for which numerous systems have been conceived.
- Tides are a result of the gravity of the sun, the moon, and the rotation of the Earth working together.
- The ocean also acts as a gigantic solar collector, capturing the energy of the sun in its surface water as heat.
- The temperature difference between warm surface waters and cold water from the ocean depths provides a **potential source of energy**. Other sources of ocean energy include ocean currents, salinity gradients, and ocean-grown biomass.

Ocean Thermal Energy Conversion

Ocean thermal energy conversion (OTEC) technology is **based on the principle that energy can be extracted from two reservoirs at different temperatures**.

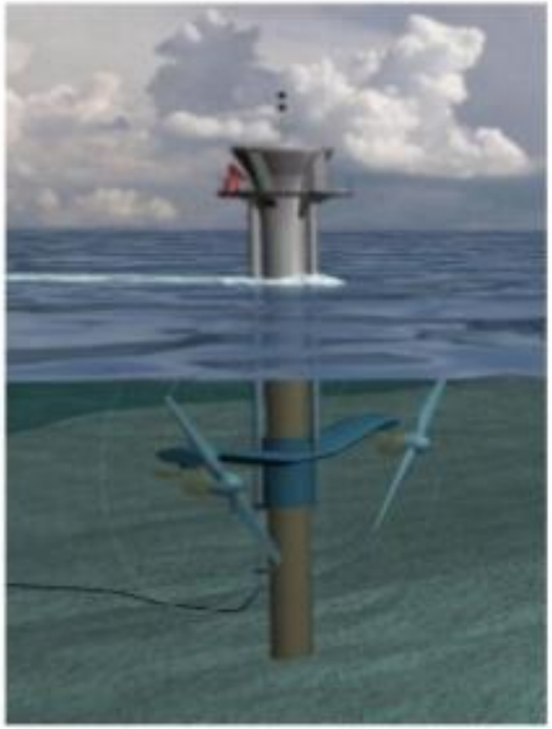
A temperature difference as little as 20°C can be exploited effectively to produce usable energy. Temperature differences of this magnitude prevail between ocean waters at the surface and at depths up to 1000 m in many areas of the world, particularly in tropical and subtropical latitudes between 24° north and south of the equator.

Here, surface water temperatures typically range from 22 to 29°C, while temperatures at a depth of 1000 m range from 4 to 6°C. This constitutes a vast, renewable resource, estimated at 1013 W, for potential baseload power generation.

Tidal Power

- The energy from tides is derived from the **kinetic energy of water moving from a higher to a lower elevation,** as for hydroelectric plants. High tide can provide the potential energy for seawater to flow into an enclosed basin or estuary that is then discharged at low tide.
- Electricity is produced from the gravity-driven inflow or outflow (or both) through a **turbo generator**.
- The tidal resource is variable but quite predictable, and there are no significant technical barriers for deployment of this technology. Because costs are strongly driven by the civil works required to dam the reservoir, only a few sites around the world have the proper conditions of tides and landscape to lend themselves to this technology.

Tidal Barrage Energy Calculations



MCT Seagen Pile

R = range (height) of tide (in m)
A = area of tidal pool (in km^2)
m = mass of water
$g = 9.81\ m/s^2$ = gravitational constant
$\rho = 1025\ kg/m^3$ = density of seawater
$\eta \cong 0.33$ = capacity factor (20-35%)

$$E = \eta mgR/2 = \eta(\rho AR)gR/2$$

$$E = 1397\eta R^2 A \quad \text{kWh per tidal cycle}$$

Assuming 706 tidal cycles per year (12 hrs 24 min per cycle)

$$E_{yr} = 0.997\times10^6 \eta R^2 A$$

Tidal Turbines

Wave Power

A myriad of wave-energy converter concepts have been devised to **transform wave energy** into other forms of mechanical (rotative, oscillating, or relative motion), potential, or pneumatic energy, and ultimately into electricity; very few have been tested at sea.

The power per unit frontal length of the wave is proportional to wave height squared and to wave period, with their representative values on the order of 2 m and 10 sec. The strong dependence on wave height makes the resource quite variable, even on a seasonal and a yearly average basis.

The northeastern Pacific and Atlantic coasts have average yearly incident wave power of about 50 kW/m, while near the tip of South America the average power can reach 100 kW/m. Japan receives an average of 15 kW/m.

Wave Power Calculations

H_s^2 = Significant wave height – 4x *rms* water elevation (m)

T_e = avg time between upward movements across mean (s)

P = Power in kW per meter of wave crest length

$$P = \frac{H_s^2 T_e}{2}$$

Example: $H_s^2 = 3\text{m}$ and $T_e = 10\text{s}$

$$P = \frac{H_s^2 T_e}{2} = \frac{3^2 \times 10}{2} = 45 \frac{kW}{m}$$

Wave Record

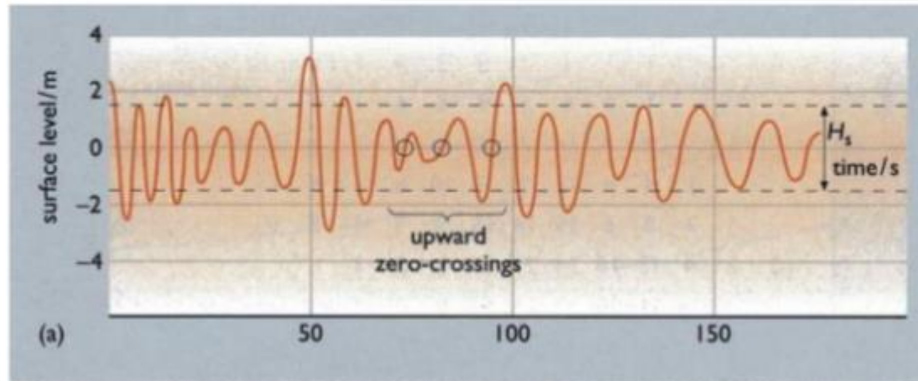


Figure 8.6 (a) A typical wave record. In this example the significant wave height H_s = 3 m.

$$P = E\, c_g = \frac{\rho g^2 A^2}{4\omega} = \frac{\rho g^2 T H^2}{32\pi}$$

With this formula, for a given wave period and height, we can compute the power that can be extracted per meter of crest of that wave.

Defining Terms

Ocean thermal energy conversion (OTEC): A system that utilizes the temperature difference between the seawater at the surface and at depths.

Closed-cycle OTEC: Uses a working fluid in a closed cycle.

Open-cycle OTEC: Uses steam flashed from the warm seawater as the working fluid which is condensed
and exhausted.

Hydroenergy

A hydraulic turbine is a mechanical device that **converts the potential energy associated with a difference in water elevation** (**head**) into useful work. Modern hydraulic turbines are the result of many years of gradual development. Economic incentives have resulted in the development of very large units (exceeding 800 mW in capacity) with efficiencies that are sometimes in excess of 95%.

The emphasis on the design and manufacture of very large turbines is shifting to the **production of smaller units, especially in developed nations**, where much of the potential for developing large-baseload plants has been realized. At the same time, the **escalation in the cost of energy has made many smaller sites economically feasible and has greatly expanded the market for smaller turbines**. Thus, a new market area is developing for updating older turbines with modern replacement **runners** having **higher efficiency and greater capacity.**

Typical Hydropower Installation

As shown schematically in Figure 8.4.1, the hydraulic components of a hydropower installation consist of an intake, penstock, guide vanes or distributor, turbine, and **draft tube**. Trash racks are commonly provided to prevent ingestion of debris into the turbine. Intakes usually require some type of shape transition to match the passageway to the turbine and also incorporate a gate or some other means of stopping the flow in case of an emergency or for turbine maintenance. Some types of turbines are set in an open flume; others are attached to a closed-conduit penstock.

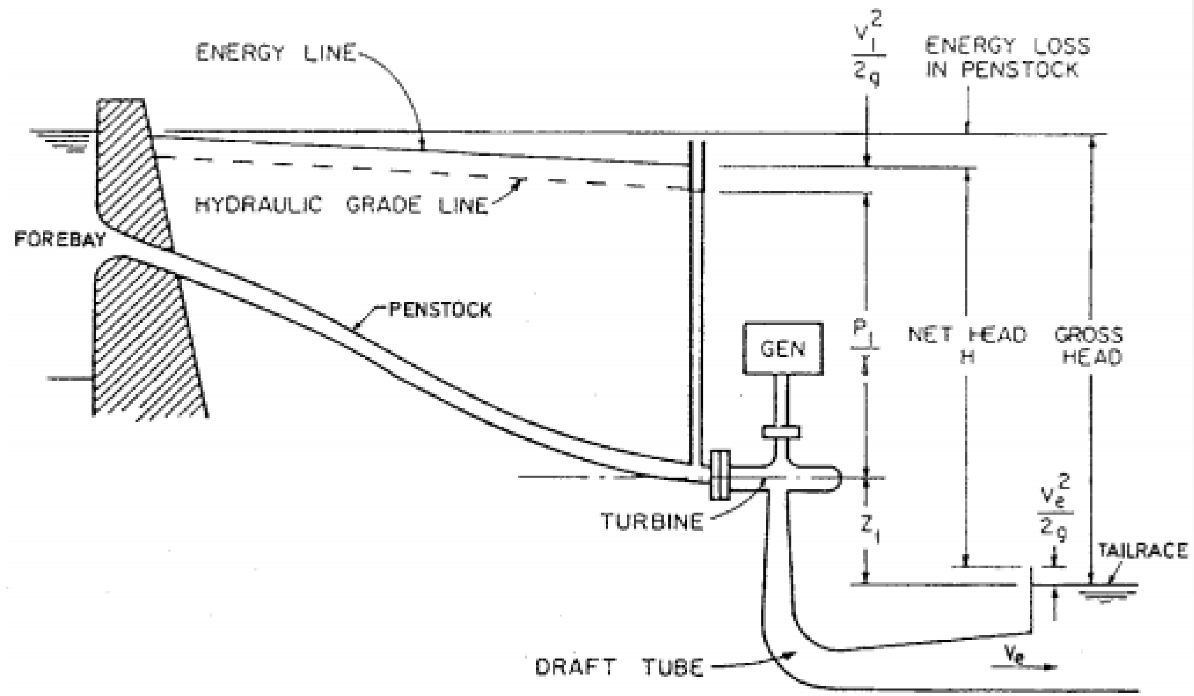


FIGURE 8.4.1 Schematic of a hydropower installation.

Turbine Classification

There are two types of turbines, denoted as impulse and reaction. In an impulse turbine, the available head is converted to kinetic energy before entering the **runner**; the power available is extracted from the flow at approximately atmospheric pressure. In a reaction turbine, the runner is completely submerged and both the pressure and the velocity decrease from inlet to outlet. The velocity head in the inlet to the turbine runner is typically less than 50% of the total head available.

Impulse Turbines. Modern impulse units are generally of the Pelton type and are restricted to relatively high-head applications (Figure 8.4.2). One or more jets of water impinge on a wheel containing many curved buckets. The jet stream is directed inward, sideways, and outward, thereby producing a force on the bucket, which in turn results in a torque on the shaft. All kinetic energy leaving the runner is "lost."

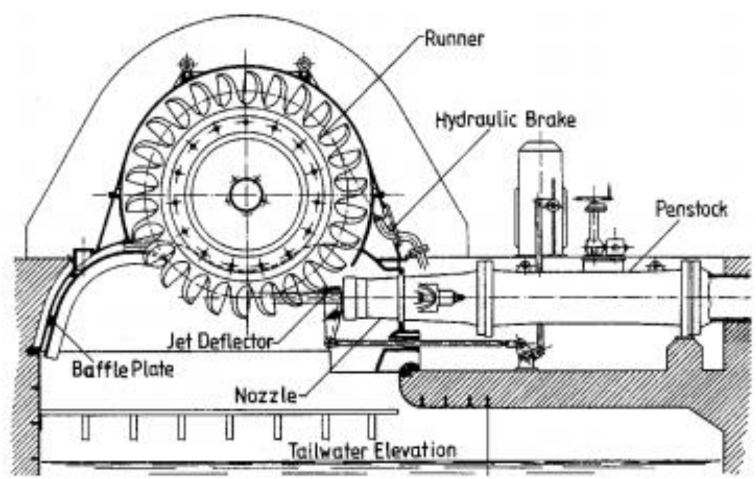


FIGURE 8.4.2 Cross section of a single wheel, single jet Pelton turbine. This is the third-highest-head pelton turbine in the world, $H = 1447$ m, $n = 500$ rpm, $P = 35.2$ MW, $N_s \sim 0.038$. (Courtesy of Vevey Charmilles Engineering Works, Adapted from J. Raabe, *Hydro Power: The Design, Use, and Function of Hydromechanical, Hydraulic, and Electrical Equipment*, VDI Verlag, Dusseldorf, Germany.)

Itaipú Dam (Brazil & Paraguay)

Efficiency of Hydropower Plants

- Hydropower is very efficient
  - Efficiency = (electrical power delivered to the "busbar") ÷ (potential energy of head water)
- Typical losses are due to
  - Frictional drag and turbulence of flow
  - Friction and magnetic losses in turbine & generator
- Overall efficiency ranges from 75-95%

https://www.slideshare.net/gaurav0191/hydro-power-plant-p

Hydropower Calculations

$$P = g \times \eta \times Q \times H$$

$$P \cong 10 \times \eta \times Q \times H$$

- P = power in kilowatts (kW)
- g = gravitational acceleration (9.81 m/s^2)
- η = turbo-generator efficiency ($0<n<1$)
- Q = quantity of water flowing (m^3/sec)
- H = effective head (m)

Defining Terms

Draft tube: The outlet conduit from a turbine which normally acts as a diffuser. This is normally considered to be an integral part of the unit.

Forebay: The hydraulic structure used to withdraw water from a reservoir or river. This can be positioned a considerable distance upstream from the turbine inlet.

Head: The specific energy per unit weight of water. *Gross head* is the difference in water surface elevation between the forebay and tailrace. *Net head* is the difference between *total head* (the sum of velocity head $V^2/2g$, pressure head $p/\rho g$, and elevation head z at the inlet and outlet of a turbine.

Some European texts use specific energy per unit mass, e.g., specific kinetic energy is $V^2/2$.

Runner: The rotating component of a turbine in which energy conversion takes place.

Specific speed: A universal number for a given machine design.

Spiral case: The inlet to a reaction turbine.

Surge tank: A hydraulic structure used to diminish overpressures in high-head facilities due to water hammer resulting from the sudden stoppage of a turbine

Wicket gates: Pivoted, streamlined guide vanes that control the flow of water to the turbine.

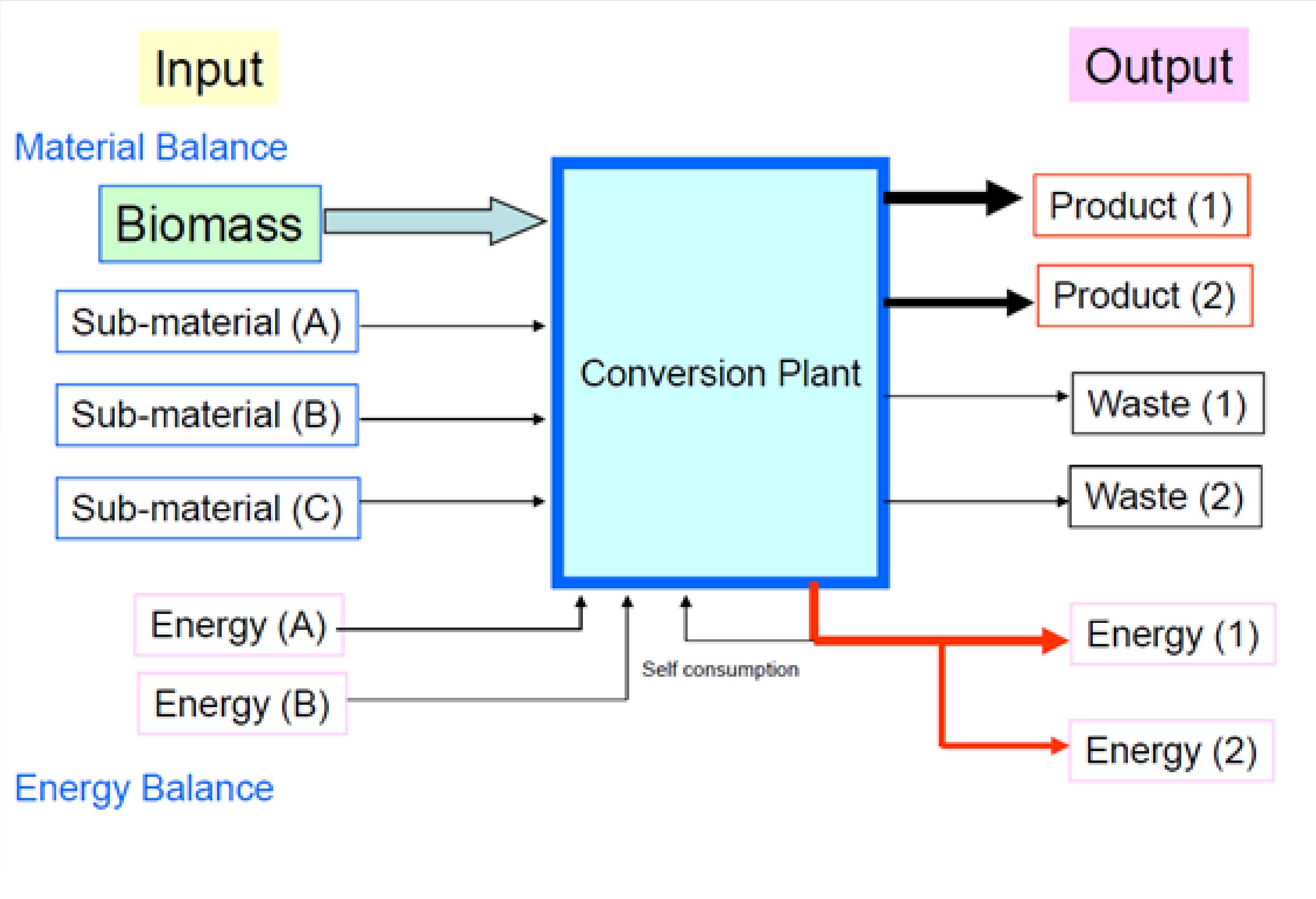
Biofuel Energy

The conversion of biomass solids into liquid or gaseous biofuels is a complex process. Today, the most common conversion processes are biochemical- and thermochemical-based. However, researchers are also exploring photobiological conversion processes.

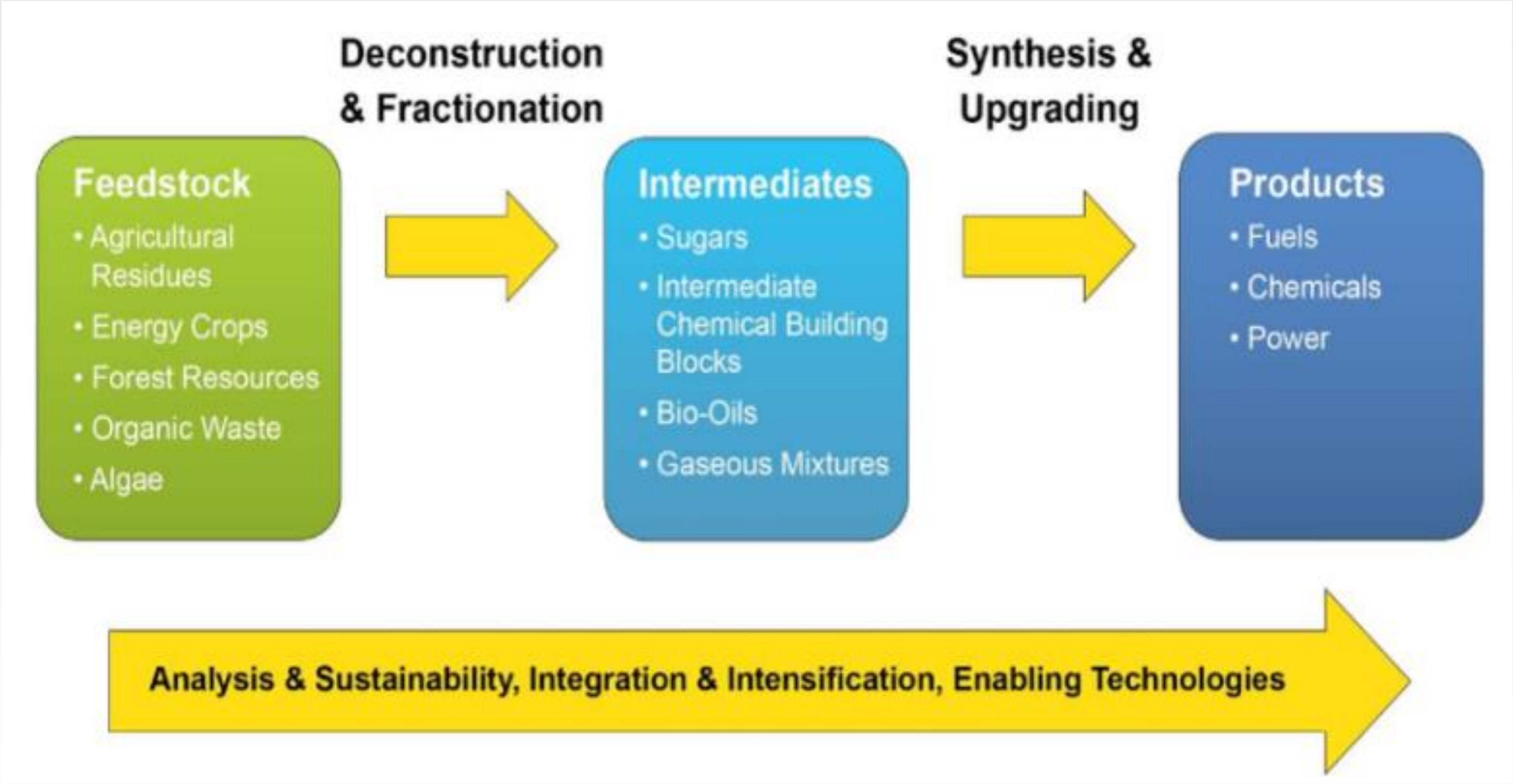
Biochemical Conversion Processes

In biochemical conversion processes, enzymes and microorganisms are used as biocatalysts to convert biomass or biomass-derived compounds into desirable products. Cellulase and hemicellulase enzymes break down the carbohydrate fractions of biomass to five- and six-carbon sugars in a process known as hydrolysis. Yeast and bacteria then ferment the sugars into products such as ethanol. Biotechnology advances are expected to lead to dramatic biochemical conversion improvements.

Biomass Conversion



Conversion Technologies



Biofuel energy

Making biodiesel - Biodiesel Production

http://farmenergymedia.extension.org/video/making-biodiesel-biodiesel-production-part-3

References

Book Chapter:
http://www.itiomar.it/pubblica/dispense/MECHANICAL%20ENGINEERING%20HANDBOOK/Ch08.pdf

https://energy.gov/eere/bioenergy

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