EES4404 : Renewable Energy and Smart Grid

Other renewable sources and Economics

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Other renewable generation sources

- Biomass
- Hydro
- Fuel Cell
- Geothermal

Biomass

Biomass for Energy

- Plants produce biomass through photosynthesis.
- Thus, Biomass contains stored chemical energy from the sun.
- Biomass can be burned directly for heat or converted to renewable liquid and gaseous fuels through various processes.

Photosynthesis

In the process of photosynthesis, plants convert radiant energy from the sun into chemical energy in the form of glucose—or sugar.

(water)		(carbon dioxide)		(sunlight)		(glucose)		(oxygen)
$6\,H_2O$	+	$6\,CO_2$	+	radiant energy	$\rightarrow$	$C_6H_{12}O_6$	+	$6\,O_2$

Source: Adapted from The National Energy Education Project (public domain)

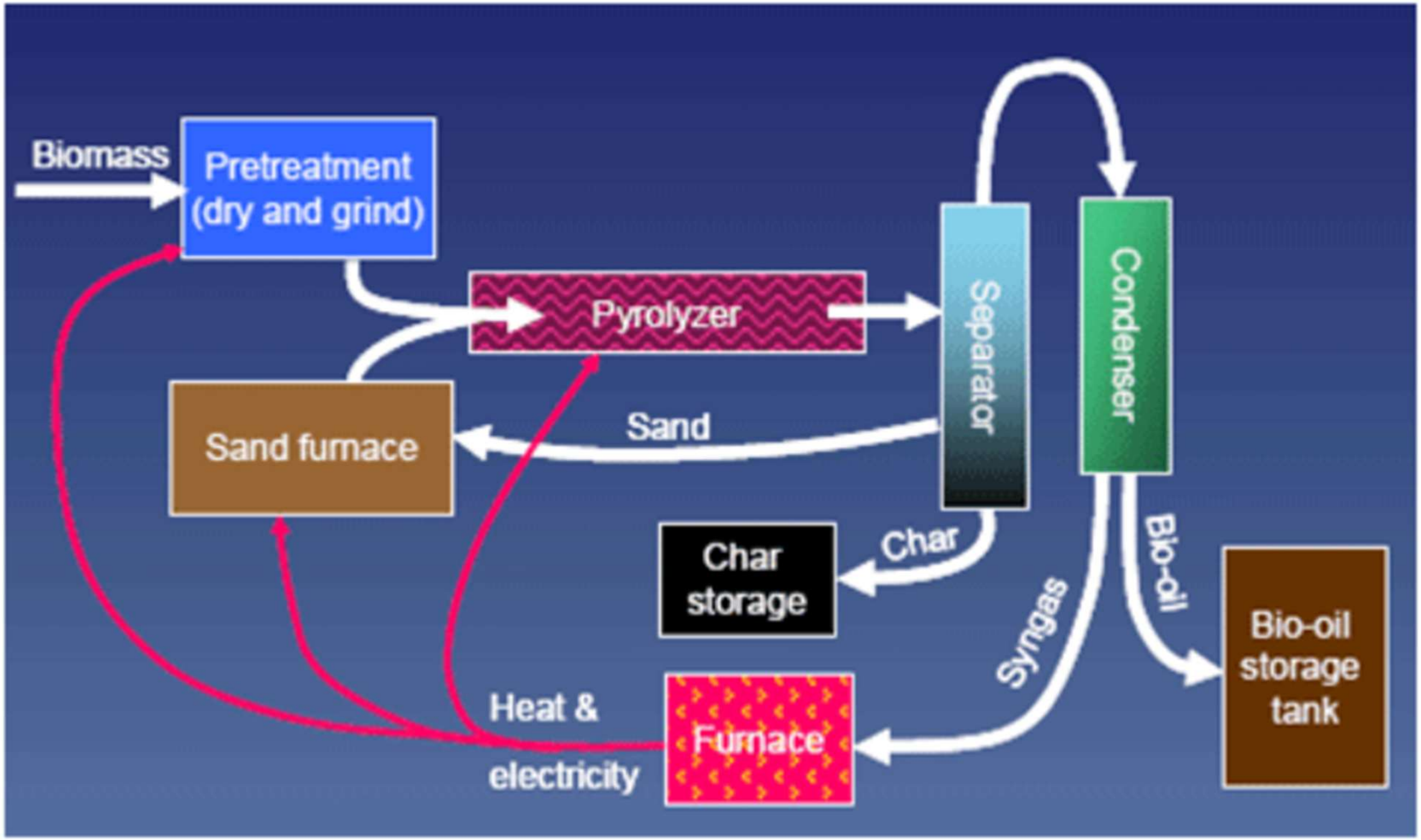
Converting biomass to energy

- Direct combustion (burning) to produce heat
- Thermochemical conversion to produce solid, gaseous, and liquid fuels
  - *pyrolysis* and
  - *gasification*.
- Chemical conversion to produce liquid fuels
- Biological conversion to produce liquid and gaseous fuels

Pyrolysis

- Pyrolysis entails heating organic materials, such as biomass to 800–900^{o}F (400–500^{o} C) in the near complete absence of free oxygen.
- Because no oxygen is present the material does not combust but the chemical compounds (i.e. cellulose, hemicellulose and lignin) that make up that material thermally decompose into combustible gases and charcoal.
- Most of these combustible gases can be condensed into a combustible liquid, called pyrolysis oil (bio-oil).
- Pyrolysis of biomass produces three products:
  1. one liquid, bio-oil,
  2. one solid, bio-char and
  3. one gaseous (syngas).

Schematic of the Fast Pyrolysis



Source: https://www.ars.usda.gov

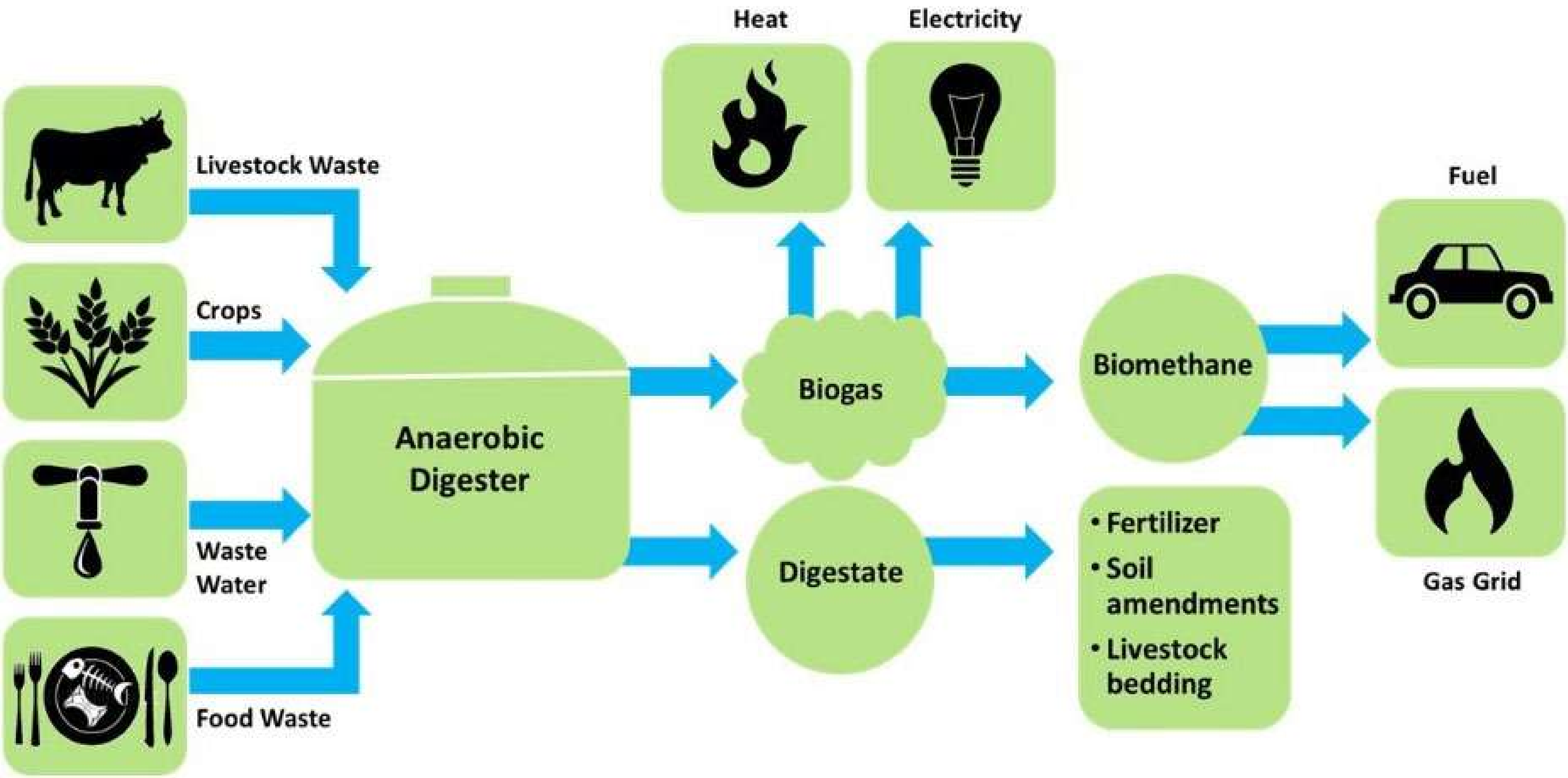
Biological conversion of biomass

- Biological conversion includes fermentation to convert biomass into ethanol and anaerobic digestion to produce renewable natural gas. Ethanol is used as a vehicle fuel.

- Renewable natural gas—also called biogas or biomethane—is produced in anaerobic digesters at sewage treatment plants and at dairy and livestock operations. It also forms in and may be captured from solid waste landfills.

- Properly treated renewable natural gas has the same uses as fossil fuel natural gas.

Anaerobic Digestion



Source: https://www.eesi.org/

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Anaerobic Digestion

- Anaerobic Digestion is a process by which organic waste materials are broken down by naturally occurring bacteria in the absence of oxygen.

- This produces Biogas, which is typically between 55%-75% methane. After impurities have been filtered, the biogas can be burned in a CHP(combined heat and power) unit to generate electricity.

- Anaerobic digesters are commonly found alongside farms to reduce nitrogen run-off from manure, or wastewater treatment facilities to reduce the costs of sludge disposal.

Advantages of Biomass

Renewable

Biomass energy is a renewable energy resource, which can be regenerated through photosynthesis of plants.

Widespread distribution

Regions lacking coal can make full use of biomass energy

Advantages of Biomass

Low polluting

- Low sulfur and nitrogen content of biomass, less SO_X and NO_X generated during combustion;
- When biomass is used as fuel, because the carbon dioxide it needs to grow is equal to the amount of carbon dioxide it emits, so the net emission of carbon dioxide to the atmosphere is approximately zero, which can effectively reduce the greenhouse effect;

The total amount is very rich

- Biomass energy is the world's fourth largest source of energy, after coal, oil and natural gas. Biologists estimate that the earth's landmasses produce between 100 and 125 billion tons of biomass annually; Oceans produce 50 billion tons of biomass a year.

Disadvantages of Biomass

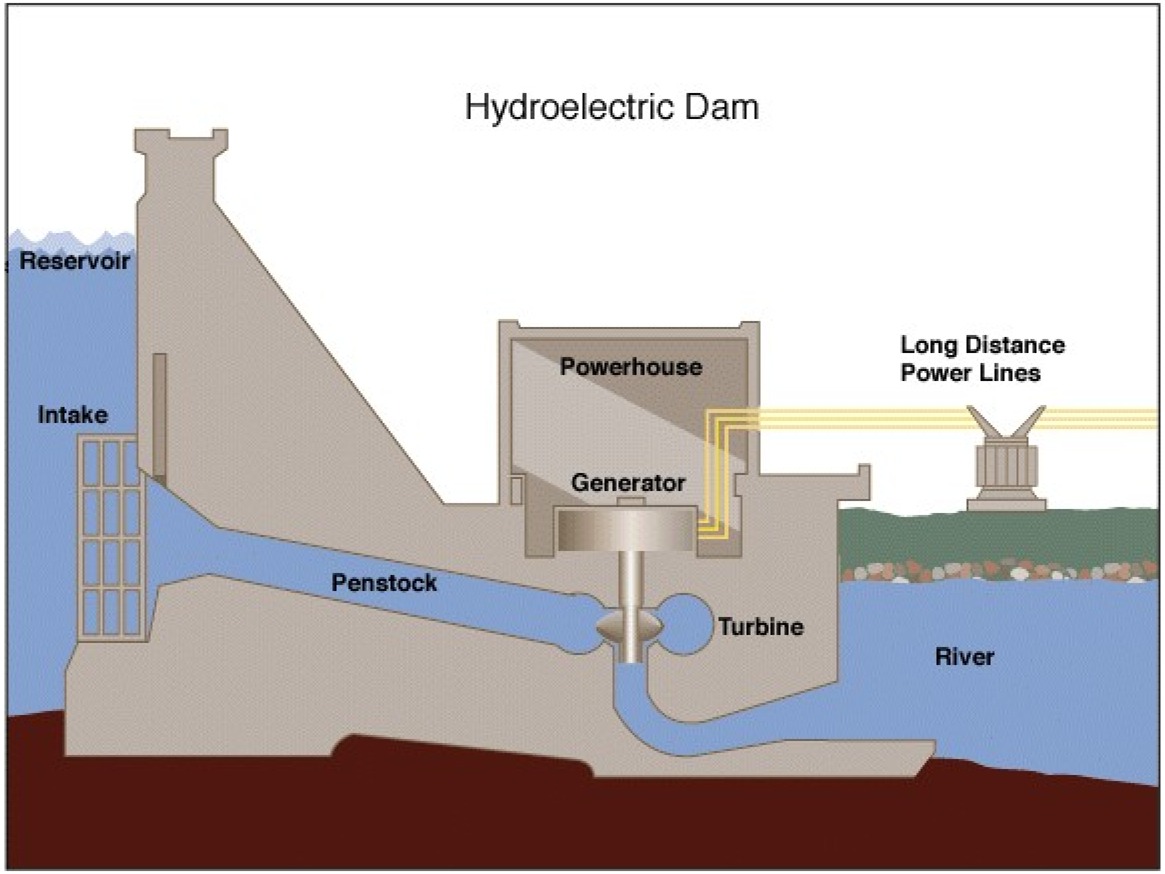
- Construction and operation costs are relatively high
- Weak technology development capacity and industrial system
- Insufficient raw materials
- Agriculture and forestry biomass is dispersed and seasonal characteristics, the current raw material collection mainly rely on artificial and small machinery, transport rely mainly on general transport, it is difficult to meet the needs of the biomass energy scale use.

Biomass for Electricity

- Biomass for electricity production is essentially all waste residues from agricultural and forestry industries and, to some extent, municipal solid wastes.
- Biomass feedstocks for electricity production may have low-cost, no-cost, or even negative-cost advantages.
- Biomass power plants tend to be small and located near their fuel source.
- Even though the fuel may be very inexpensive, those low efficiencies translate to reasonably expensive electricity due to very low efficiency.

Hydro Power

Hydro Power



- Hydroelectric power is a very significant source, accounting for 19% of the global production of electricity.
- Almost all the hydropower is generated in large-scale projects, which are sometimes defined to be those larger than 30 MW in capacity.

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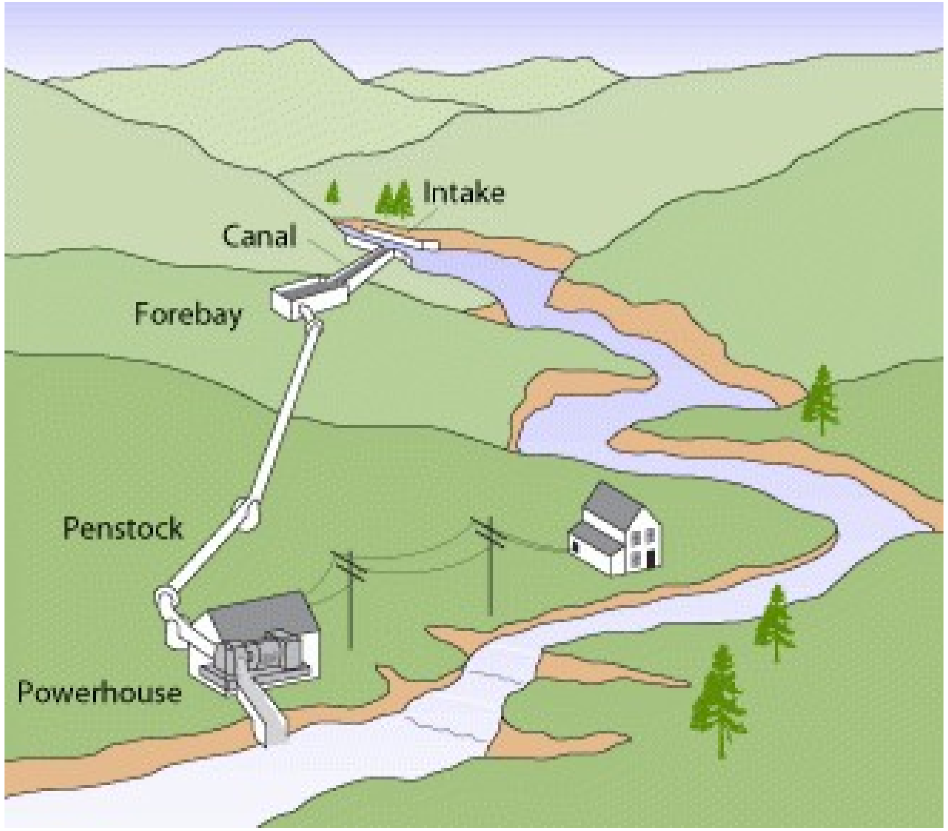
Micro-Hydropower Systems

- Small-scale hydropower systems are considered to be those that generate between 100 kW and 30 MW, while micro-hydro plants are smaller than 100 kW.

- Run-of-the-river systems don't cause nearly the ecosystem disruption of their dams and reservoir counterparts.



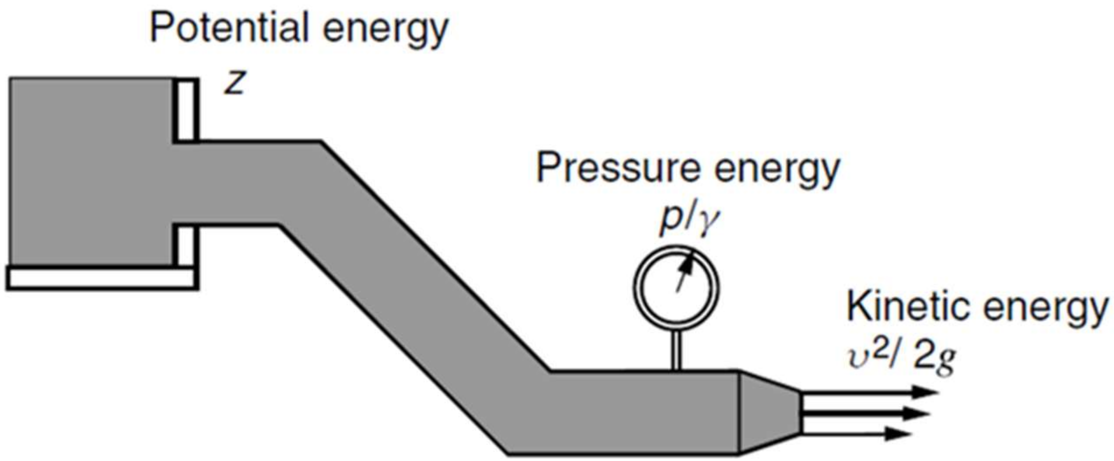
Run-of-the-river systems

Power From a Micro-Hydro Plant

The energy associated with water manifests itself in three ways:

as potential energy (mgz due to the water level in the dam) pressure energy (pV in the penstock) and kinetic energy ($\frac{1}{2}mv^2$ as water flows).

m – mass
g – acceleration due to gravity
z – elevation of water
p – pressure
V – Volume
v – velcity pf water



Transformation of energy from potential, to pressure, to kinetic

Energy head

- Each energy type is divided by weight (mg) to get energy per unit weight, which is known as energy head.
- It has dimension of length.
- Energy head, $\mathrm{H} = z + \frac{p}{\gamma} + \frac{v^2}{2g}$

where,

z is the elevation above a reference height (m),

p is the pressure (N/m^2),

γ is specific weight (N/m^3),

v is the average velocity (m/s)

g is gravitational acceleration (m/s^2)

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Power From a Micro-Hydro Plant

The power theoretically available from a site is proportional to the difference in elevation between the source and the turbine, called the head H, times the rate at which water flows from one to the other, Q.

$$Power = \frac{Energy}{Time} = \frac{Weight}{Voume} \times \frac{Volume}{Time} \times \frac{Energy}{Weight} = \rho g Q H$$

where,

$Power$ in (W)

ρ is density (Kg/m^3)

g is gravitational acceleration (m/s^2)

Q is volume flow rate (m^3/s)

H is the head (m)

Example

Suppose a 10 cm diameter penstock delivers 450 litres per minute of water through an elevation change of 30 meter.

The pressure in the pipe is 200 kN/m^2 when it reaches the powerhouse.

i. What fraction of the available head is lost in the pipe?

ii. What power is available for the turbine?

Solution

Flow rate is 450 litres/min. Pressure in pipe near power house is 200kN/m^2

$$v = \frac{Flow\left(\frac{litres}{min}\right)\times 10^{-3}}{60\times A(m^2)}\ m/sec$$

$$A = \pi\frac{D^2}{4} = \pi\frac{0.1^2}{4}\ \mathrm{m}^2$$

$$v = \frac{450\times 10^{-3}\times 4}{60\times\pi\times 0.01} = 0.955\ m/sec$$

$$\gamma = 9810\ N/m^3$$

Head at the turbine = $\frac{p}{\gamma} + \frac{v^2}{2g} = \frac{200\times 10^3}{9810} + \frac{0.955^2}{2\times 9.81} = 20.44m$

i. Head lost in pipe $H = 30 - 20.44 \approx 9.56$ m i.e. 31.87% of the total head

ii. Power available for the turbine :

$$\rho gQH = 1000\times 9.81\times\frac{450}{60}\times 10^{-3}\times 20.44 = 1503.88W$$

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Home scale hydro plants

- With a high-head site, lower flow rates translate into smaller diameter piping, which is more readily available and a lot easier to work with, as well as smaller, less expensive turbines.
- Home-scale projects with modest flows and decent heads can lead to quick, simple, cost-effective systems.
- There will be pipe losses. PVC pipe has lower friction losses and it is also less expensive than polyethylene pipe.
- The cost of the piping is often a significant fraction of the total cost of a micro-hydro project.
- Efficiency of turbine-generator is about 50%.
- Power delivered from the plant $\approx 0.5\rho g Q H$

Turbines

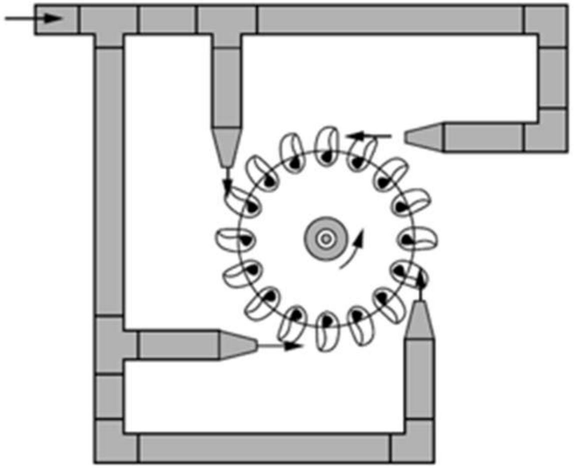
- Energy in water manifests itself in three forms—potential, pressure, and kinetic head.

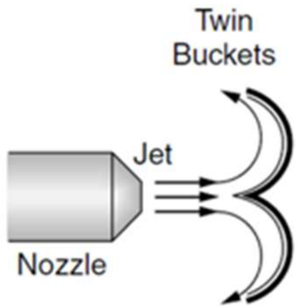
- Three different approaches to transforming that waterpower into the mechanical energy of the turbine
  - *Impulse turbines* capture the kinetic energy of high-speed jets of water squirting onto buckets along the circumference of a wheel.
  - In a *reaction turbine* it is mostly the pressure difference across the runners, or blades, of these turbines that create the desired torque.
  - *Waterwheel* converts potential energy into mechanical energy. Due to its slowness, it is not used in the generation of electricity.

- Impulse turbines are the most commonly used turbines in micro-hydro systems.

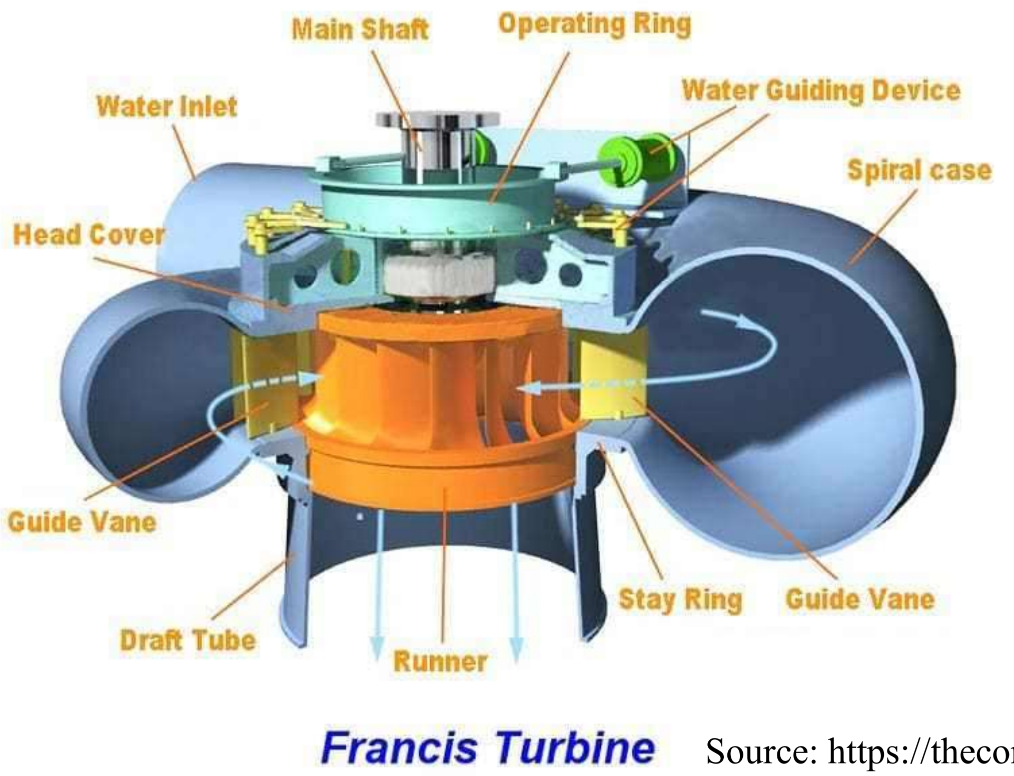
Pelton turbine

- In a Pelton wheel, water squirts out of nozzles onto sets of twin buckets attached to the rotating wheel.
- It is a type of impulse turbine.
- These turbines have efficiencies typically in the range of 70–90%





Francis turbine



Source: https://theconstructor.org/

It is an inward-flow reaction turbine that combines radial and axial flow concepts.

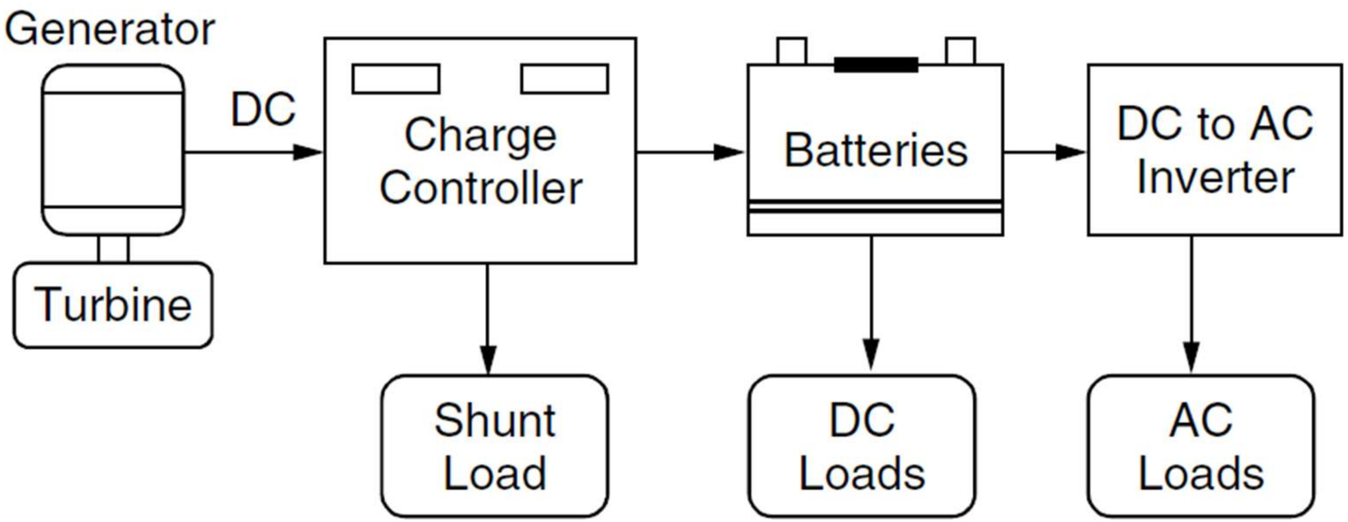
Reaction turbines

- For low-head installations with large flow rates, reaction turbines are commonly used.
- Reaction turbine runners are completely immersed in water and derive their power from the mass of water moving through them rather than the velocity.
- Reaction turbines used in micro-hydro installations have runners that look like an outboard motor propeller.
- The propeller may have three to six blades, with fixed pitch.
- Larger units that include variable-pitch blades and other adjustable features are referred to as Kaplan turbines.

Kaplan turbine (Propeller type)

Electrical part of micro-hydro

- Larger micro-hydro systems may be used as a source of ac power that is fed directly into utility lines using conventional synchronous generators and grid interfaces.
- On the other end of the scale, home-size micro-hydro systems usually generate dc, which is used to charge batteries.



Fuel Cells

Fuel Cells

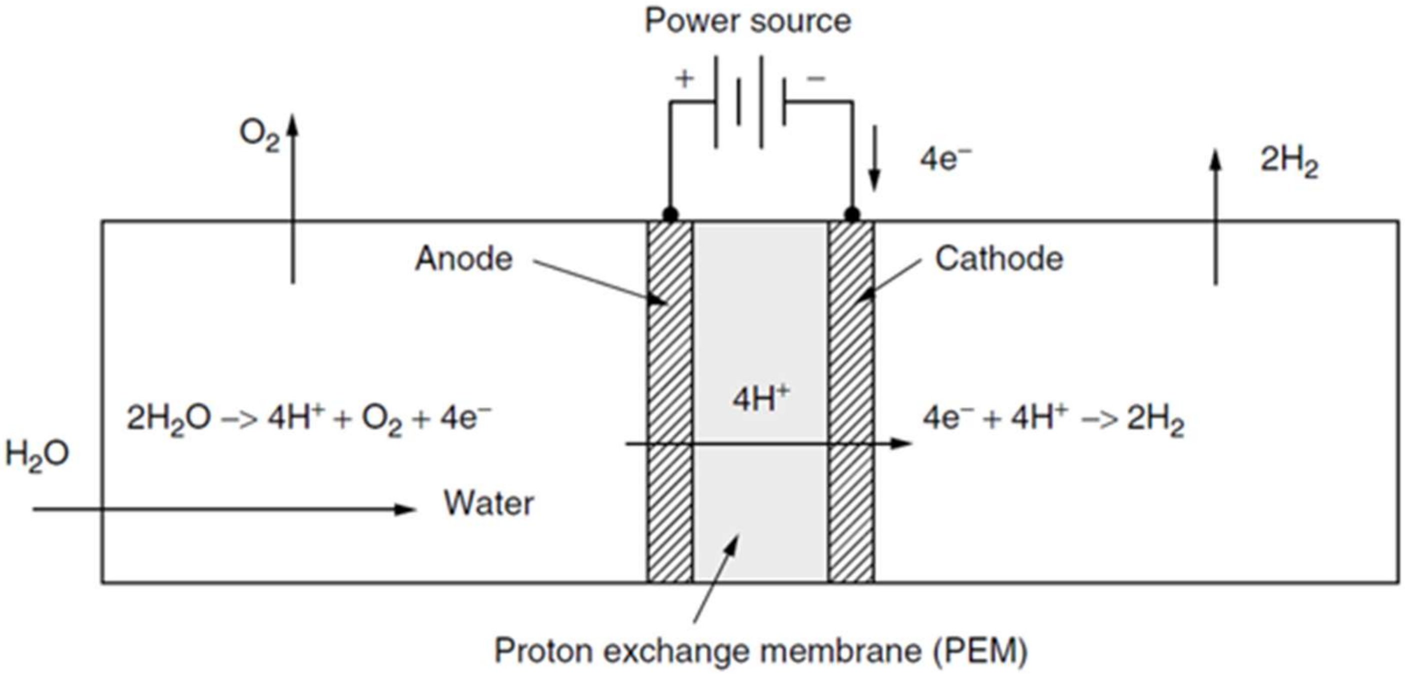
- Fuel cells convert chemical energy contained in a fuel (hydrogen, natural gas, methanol, gasoline, etc.) directly into electrical power.
- Fuel-to-electric power efficiencies as high as 65% are likely, roughly twice as efficient as the average central thermal power stations.
- The usual combustion products (SO_x, particulates, CO, and various unburned or partially burned hydrocarbons) are not emitted.
- They are inherently modular in nature, so that small amounts of generation capacity can be added as loads grow.

Hydrogen as a fuel

- Hydrogen as a fuel when burned, the end-product is water.
- Given its low density, it readily escapes from confined environments so that it is less likely to concentrate in dangerous pools.
- Almost all fuel cells require a source of hydrogen H_2 for the anodic reactions.
- Methane may be reformed to yield hydrogen as part of the fuel cell system itself;
- Obtaining a supply of hydrogen of sufficient purity and at a reasonable cost is a major hurdle that must be dealt with before large-scale commercialization of fuel cells will be achieved.

Electrolysis of Water

- When an electrical current is forced through water added with an electrolyte, water molecules can be broken apart, releasing hydrogen and oxygen gases: $2H_2O \longrightarrow 2H_2 + O_2$



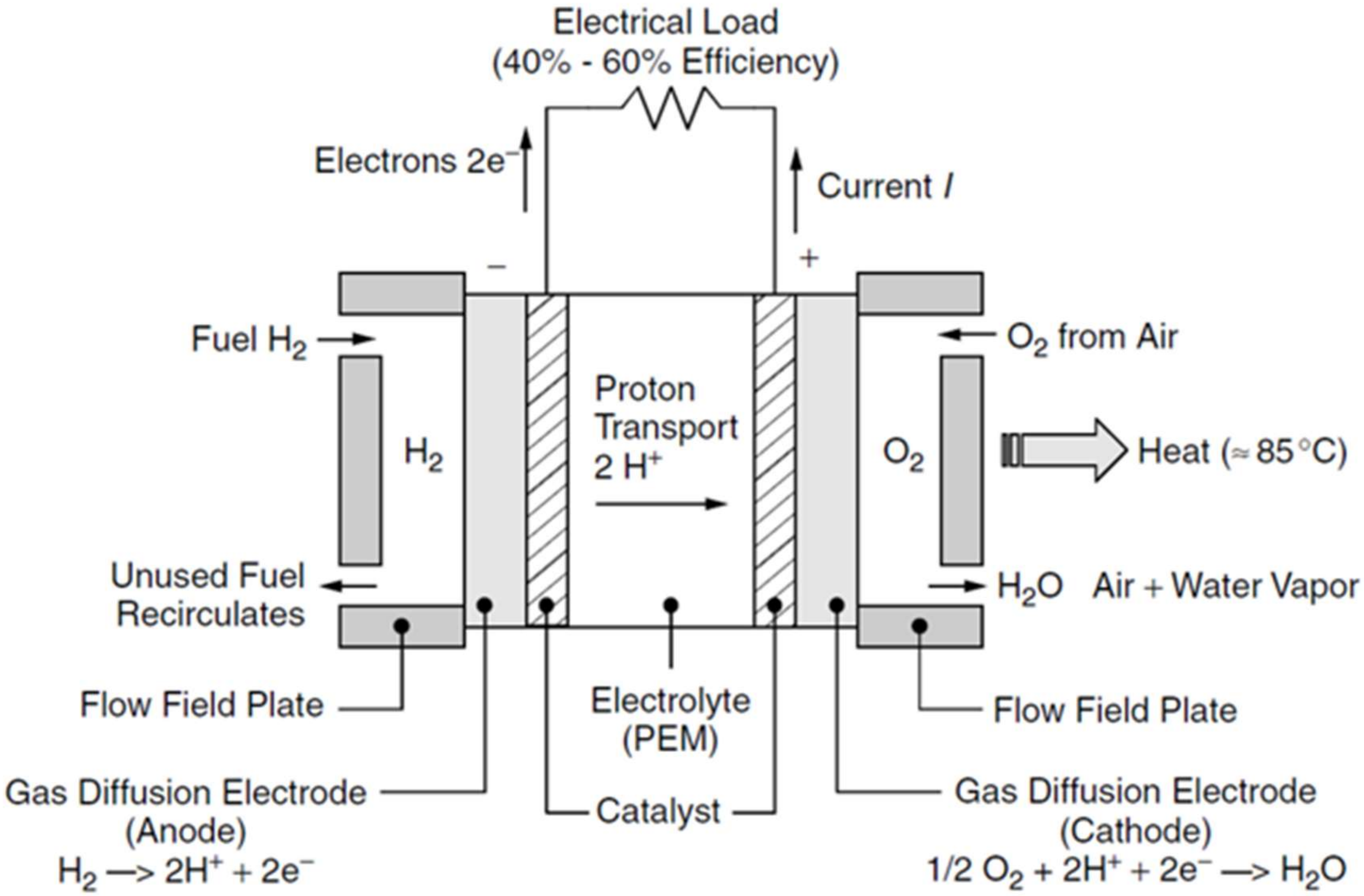
Electrolysis of Water

- De-ionized water introduced into the oxygen side of the cell dissociates into protons, electrons, and oxygen.
- The oxygen is liberated, the protons pass through the membrane, and the electrons take the external path through the power source to reach the cathode where they reunite with protons to form hydrogen gas.
- Overall efficiency can be as high as 85%.
- When the electricity for electrolysis is generated using a renewable energy system, such as wind, hydro, or photovoltaic power, hydrogen is produced without emission of any greenhouse gases.

Types of Fuel Cells

- Proton Exchange Membrane Fuel Cells (PEMFC)
- Direct Methanol Fuel Cells (DMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Alkaline Fuel Cells (AFC)
- Molten-Carbonate Fuel Cells (MCFC)
- Solid Oxide Fuel Cells (SOFC)

Basic Operation of Fuel Cells



Basic Operation of Fuel Cells

- A single cell consists of two porous gas diffusion electrodes separated by an electrolyte.
- It is the choice of electrolyte that distinguishes one fuel cell type from another.
- The electrolyte consists of a thin membrane that is capable of conducting positive ions but not electrons or neutral gases.
- The entering hydrogen gas has a slight tendency to dissociate into protons and electrons as follows:

$$H_2 \leftrightarrow 2H^+ + 2e^-$$

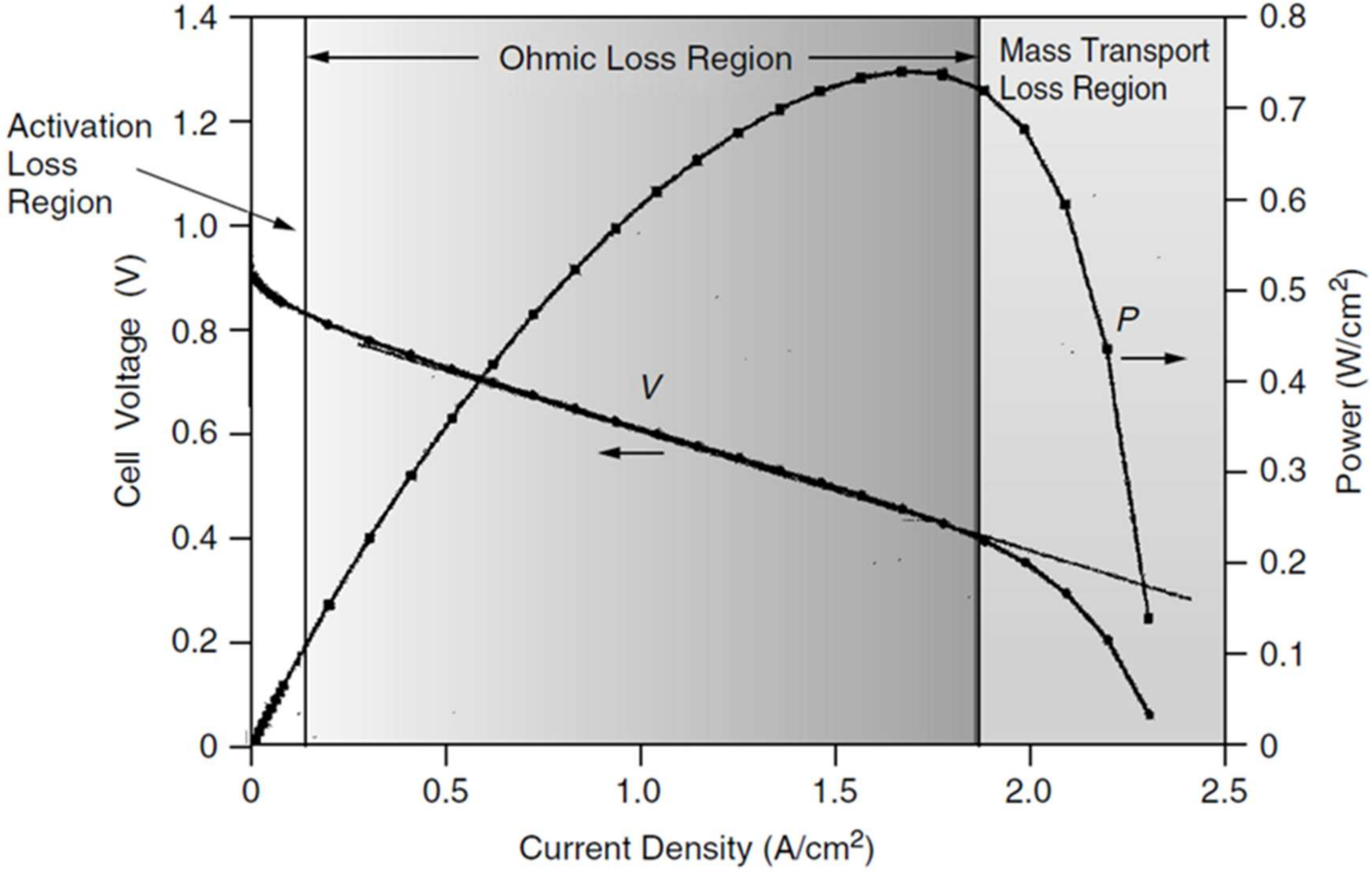
- This dissociation can be encouraged by coating the electrodes or membrane with catalysts to help drive the reaction to the right.

Losses in the Fuel Cell

- *Activation losses* result from the energy required by the catalysts to initiate the reactions. The relatively slow speed of reactions at the cathode, where oxygen combines with protons and electrons to form water, tends to limit fuel cell power.
- *Ohmic* losses result from current passing through the internal resistance posed by the electrolyte membrane, electrodes, and various interconnections in the cell.
- Another loss, referred to as *fuel crossover*, results from fuel passing through the electrolyte without releasing its electrons to the external circuit.
- And finally, *mass transport losses* result when hydrogen and oxygen gases have difficulty reaching the electrodes. This is especially true at the cathode if water is allowed to build up, clogging the catalyst.

- For these and other reasons, real fuel cells, in general, generate only about 60–70% of the theoretical maximum.

Electrical Characteristics of Real Fuel Cells



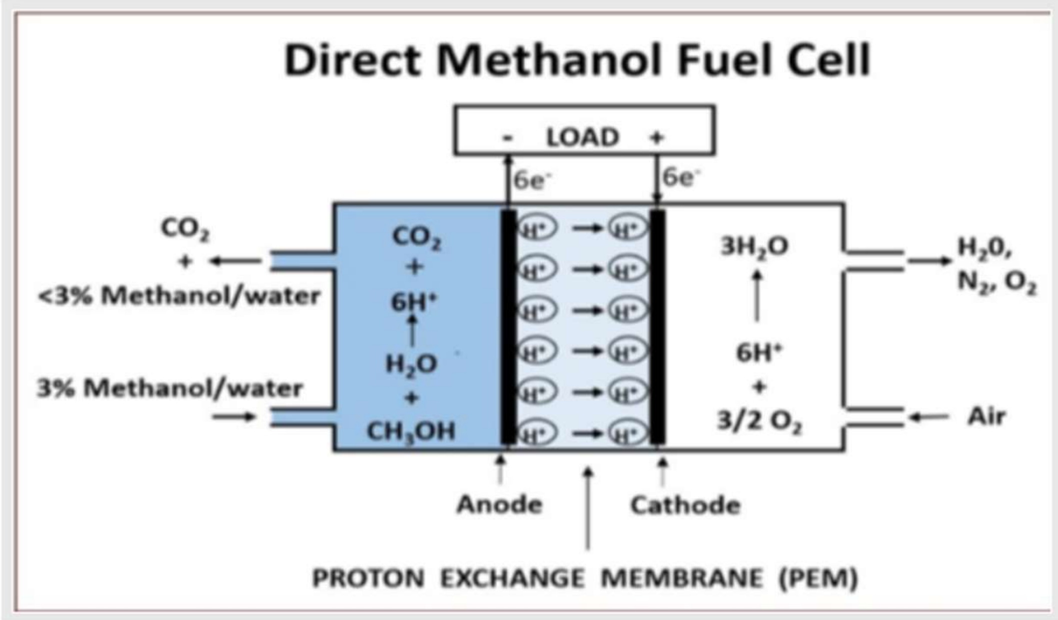
Proton Exchange Membrane Fuel Cell (PEMFC)

- Called *polymer electrolyte membrane* fuel cells
- Leading candidates for use in hybrid electric vehicles (HEVs).
- Their efficiencies are the highest available at around 45%
- Currently operating units range in size from 30 W to 250 kW.
- PEM cells generate over 0.5 W/cm^2 of membrane at around 0.65 V per cell and a current density of 1 A/cm^2.

Direct Methanol Fuel Cell (DMFC)

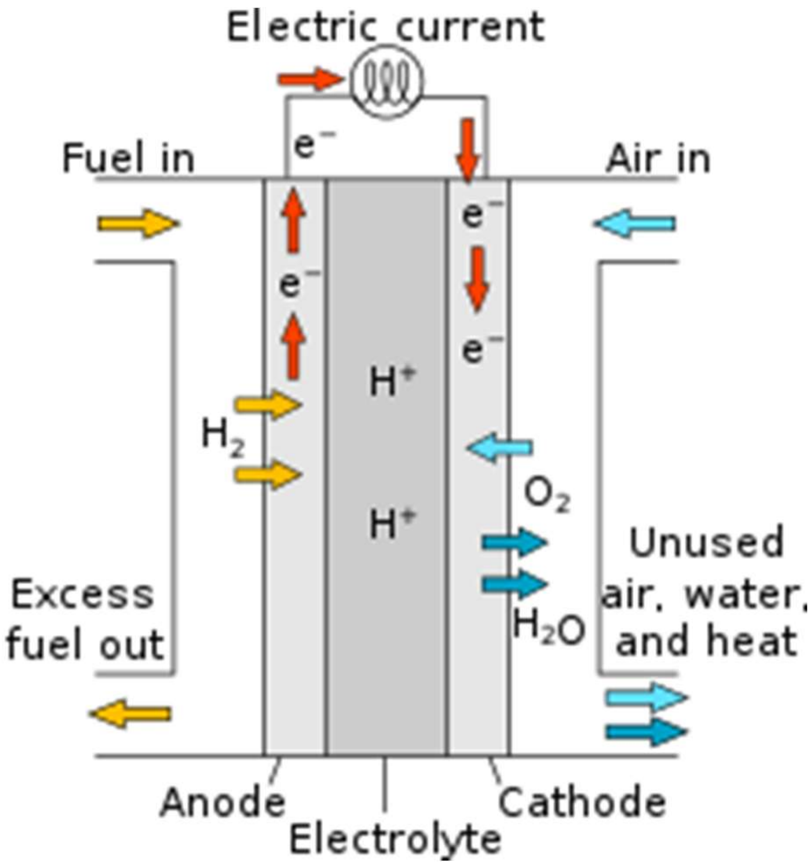
- These cells use the same polymer electrolytes as PEM cells do, but they offer the significant advantage of being able to utilize a liquid fuel, methanol (CH_3OH), instead of gaseous hydrogen.

- Liquid fuels are much more convenient for portable applications such as motor vehicles as well as small, portable power sources for everything from cell phones and laptop computers to replacements for diesel-engine generators.



Phosphoric Acid Fuel Cell (PAFC)

- The electrochemical reactions taking place in a PAFC are the same as in a PEM cell, but the electrolyte is phosphoric acid rather than a proton exchange membrane.
- Electrolyte is highly concentrated or pure liquid phosphoric acid (H_3PO_4) saturated in a silicon carbide matrix (SiC).
- Operating range is about 150 to 210 °C.
- The electrodes are made of carbon paper coated with a finely dispersed platinum catalyst.
- These cells tolerate CO better than PEM cells, but they are quite sensitive to H_2S.

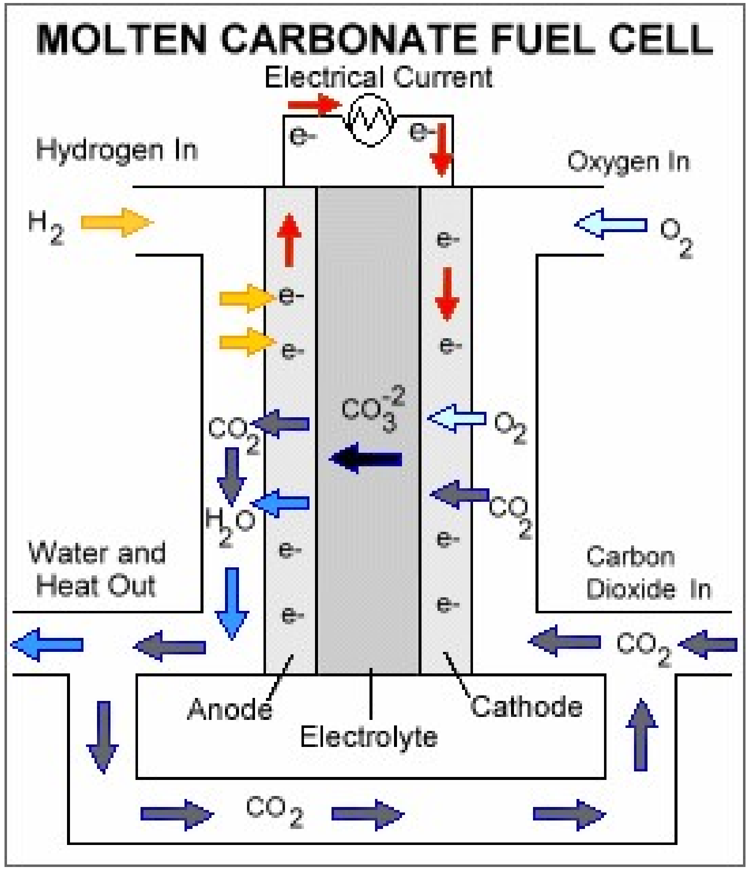


Alkaline Fuel Cell (AFC)

- Their electrolyte is potassium hydroxide (KOH), and the charge carrier is OH^- rather than H^+ ions.
- The two electrodes are separated by a porous matrix saturated with an aqueous alkaline solution, such as potassium hydroxide (KOH).
  - Aqueous alkaline solutions do not reject carbon dioxide (CO_2) so the fuel cell can become "poisoned" through the conversion of KOH to potassium carbonate (K_2CO_3). Because of this, alkaline fuel cells typically operate on pure oxygen
- Since air is the source of O_2 for the cathodic reactions, it is unlikely that these will be used in terrestrial applications.
- These are highly efficient and reliable fuel cells that were developed for the Apollo and Space Shuttle programs.

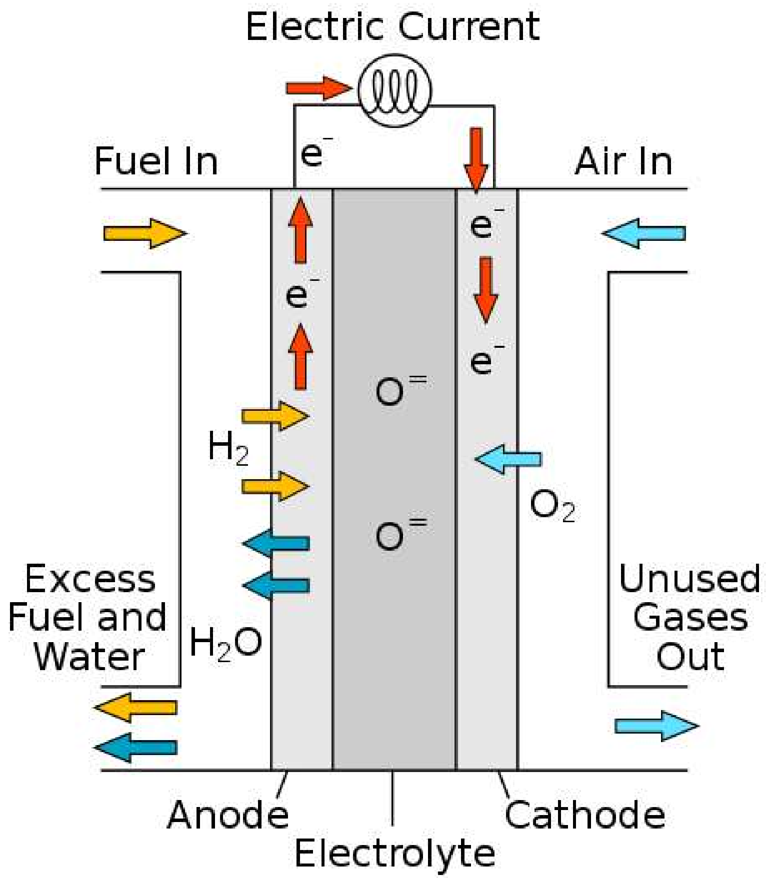
Molten-Carbonate Fuel Cells (MCFC)

- Molten-carbonate fuel cells (MCFCs) are high-temperature fuel cells that operate at temperatures of 600 °C and above.
- Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen.
- Due to the high temperatures, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.
- MCFC is currently being developed for natural gas, biogas (produced as a result of anaerobic digestion or biomass gasification), and coal-based power plants for electrical utility, industrial, and military applications.



Solid Oxide Fuel Cells (SOFC)

- SOFCs use a solid oxide electrolyte to conduct negative oxygen ions from the cathode to the anode.
- They operate at very high temperatures, typically between 600 and 1,000 °C.
- At these temperatures, SOFCs do not require expensive platinum catalyst material, and are not vulnerable to carbon monoxide catalyst poisoning.
- This type of fuel cells have high combined heat and power efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost.
- The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues.



Comparison of Fuel Cell Technologies

Fuel Cell Type	Operating Temp (^{o}C)	System Output (kW)	Electrical Efficiency (%)	CHP efficiency (%)	Applications
Alkaline (AFC)	90-100	10-100	60	>80	Military and Space
Phosphoric Acid (PAFC)	150-200	50-1000	>40	>85	Distributed generation
Solid Oxide (SOFC)	600-1000	100-3000	35-43	<90	Electric utility, Large distributed generation
Molten Carbonate (MCFC)	600-700	100-1000	45-47	>80	Electric utility, Large distributed generation
Polymer Electrolyte Membrane (PEM)	50-100	1-250	53-58	70-90	Backup power, Portable power, Small distributed Generation, Specially vehicle Transportation
Direct methanol fuel cell (DMFC)	60-200	0.001-100	40	80	Replace batteries in mobiles; computers and other portable devices

Application of Fuel Cell

- Emission minimization or elimination
- For areas with limited access to utility grid
- For biological waste gases management

Geothermal Energy

Geothermal Energy

- Geothermal energy is heat within the earth.
- Geothermal energy is a renewable energy source because heat is continuously produced inside the earth. The slow decay of radioactive particles in the earth's core, a process that happens in all rocks, produces geothermal energy.
- Most geothermal resources are near the boundaries of the earth's tectonic plates
- People use geothermal heat for bathing, to heat buildings, and to generate electricity.

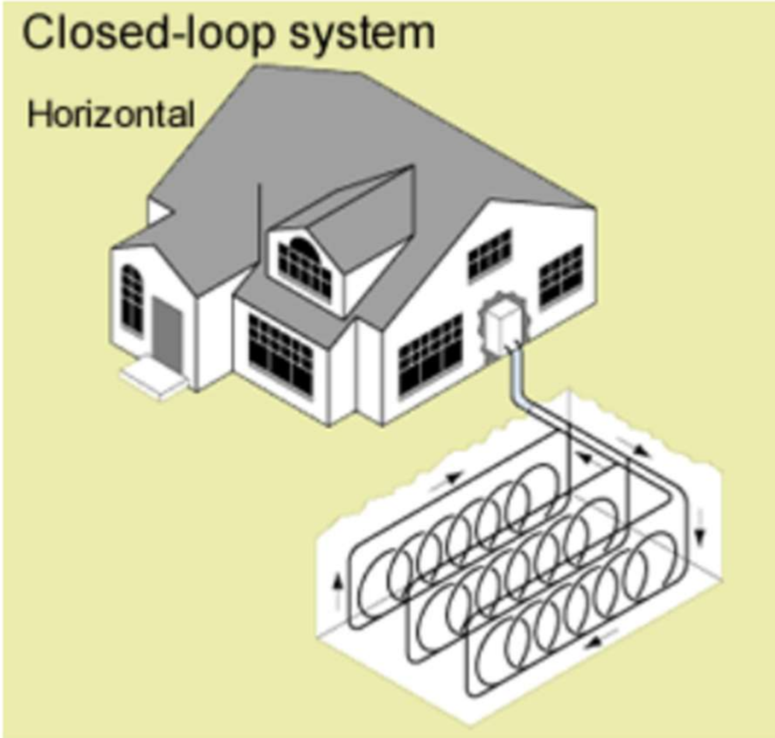
Types of geothermal power plants

1. Dry steam plants use steam directly from a geothermal reservoir to turn generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy, where natural steam erupted from the earth.
2. Flash steam plants take high-pressure hot water from deep inside the earth and convert it to steam to drive generator turbines. Most geothermal power plants are flash steam plants.
3. Binary cycle power plants transfer the heat from geothermal hot water to another liquid. The heat causes the second liquid to turn to steam, which is used to drive a generator turbine.

Source: U.S. Department of Energy,

Geothermal heat pumps

- Although air temperatures above ground change throughout the day and with the seasons, temperatures of the earth 10 feet below ground are constant.
- Geothermal heat pumps use the earth's constant temperature to heat and cool buildings.
- Geothermal heat pumps transfer heat from the ground (or water) into buildings during the winter and reverse the process in the summer.



A type of geothermal heat pump system

Source: U.S. Department of Energy, Office of Energy

Economics of distributed generation

Integrated resource planning (IRP)

Traditional power planning

Forecasting demand by extrapolating existing trends, and then trying to select the most cost-effective combination of new power plants to meet that forecast.

Integrated resource planning (IRP)

Both supply-side and demand-side resources are evaluated, including environmental and social costs, to come up with a least-cost plan to meet the wants and needs of customers for energy services.

Three kinds of electricity resources

1. **Generation resources**

   Adopting new distributed generation , small scale and located near the end-use

2. **Grid resources**

   Reducing grid losses by improving power factor

3. **Demand-side resources**

   Using electricity more efficiently for energy services E.g. illumination efficiency can be improved by replacing the incandescent bulbs with fluorescent lamps of LED lights. Use of more efficient motors in industrial applications

Electric Utility Rate Structures

- Economic viability calculation for a distributed resource (DR) project is a careful analysis of the cost of electricity and/or fuel that will be displaced by the proposed system.

- Electric rates vary considerably based on the electrical characteristics of the specific customer purchasing the power.

Rate variation for different types of customers

- Residential customer will typically include a basic fee to cover costs of billing, meters, and other equipment, plus an energy charge based on the number of kilowatt-hours of energy used.
- Commercial and industrial customers are usually billed not only for energy (kilowatt-hours) but also for the peak amount of power that they use (kilowatts) known as *demand charge* for power ($/mo per kW).
- Large industrial customers may also pay additional fees if their power factor—that is, the phase angle between the voltage supplied and the current drawn—is outside of certain bounds.

Standard Residential Rates

Tier Level	Winter: November–April		Summer: May–October	
Tier I	First 620kWh	7.378¢/kWh	First 700kWh	8.058¢/kWh
Tier II	621–825	12.995¢/kWh	701–1000	13.965¢/kWh
Tier III	Over 825	14.231¢/kWh	Over 1000	15.688¢/kWh

- Customers are categorised in terms of range of consumption.
- The rates increase with increasing demand – known as inverted block rate structure.
- It is designed to discourage excessive consumption.

Example

Suppose that a customer who uses 1200 kWh/month in summer and is subject to the rate structure as given below:

Tier Level	Winter: November–April		Summer: May–October	
Tier I	First 620kWh	7.378¢/kWh	First 700kWh	8.058¢/kWh
Tier II	621–825	12.995¢/kWh	701–1000	13.965¢/kWh
Tier III	Over 825	14.231¢/kWh	Over 1000	15.688¢/kWh

What would be the total cost of electricity ($/month) ignoring the monthly service charges?

Solution

The total monthly bill includes:

700 kWh @8.05¢,

300 kWh @13.96¢, and

200kWh @15.688¢:

Total bill:

$$700 \times \$0.08058 + 300 \times \$0.13965 + 200 \times \$0.15688 = \$129.68/month$$

Residential Time-of-Use (TOU) Rates

- In an effort to encourage customers to shift their loads away from the peak demand times, some utilities are beginning to offer residential time-of-use (TOU) rates.

- TOU rates in such circumstances charge more for electricity during summer afternoons when many air conditioners are used.

- Conversely, at night when there is idle capacity, rates may be significantly lower.

Residential Time-of-Use (TOU) Rates

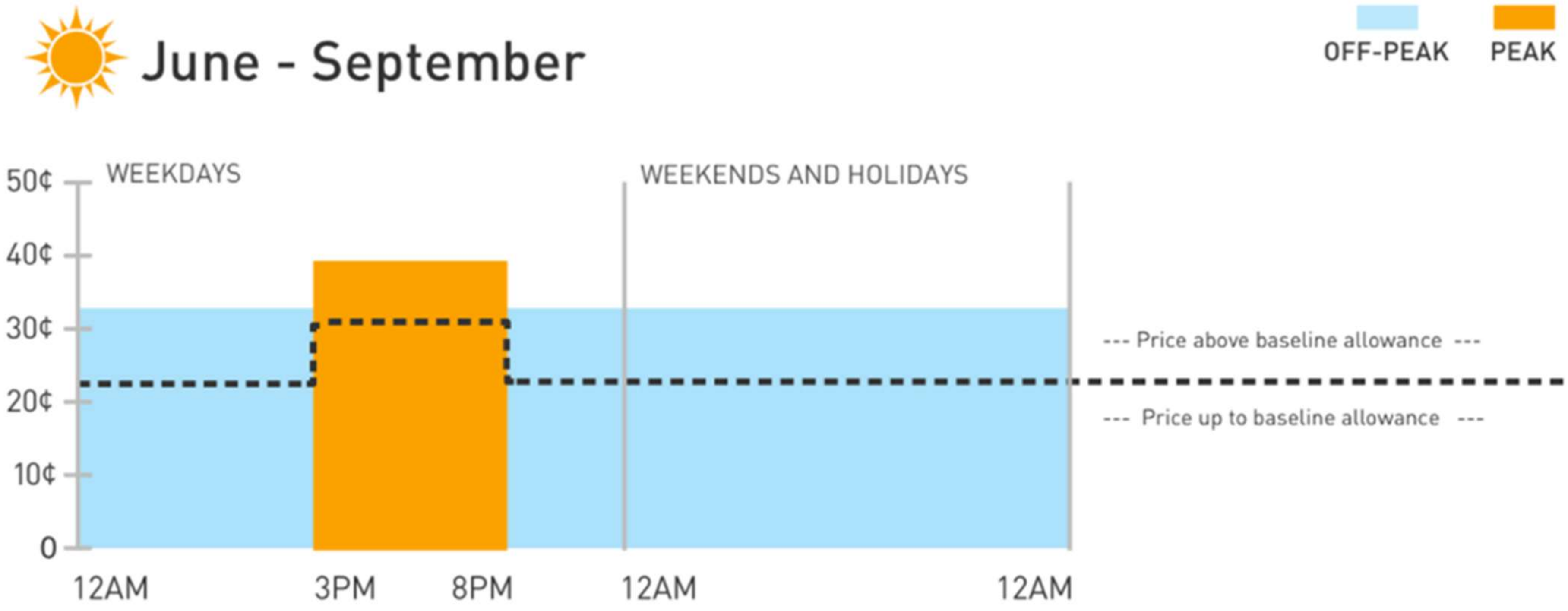


TABLE 5.2 Example Residential Time-of-Use (TOU) Rate Schedule

	November–April		May–October	
On-peak	7–10 A.M., 5–8 P.M.	8.335 ¢/kWh	2–8 P.M.	19.793 ¢/kWh
Off-peak	All other times	7.491 ¢/kWh	All other times	8.514 ¢/kWh

Example 5.2 PVs, TOU Rates, and Net Metering. During the summer a rooftop PV system generates 10 kWh/day during the off-peak hours and 10 kWh/day during the on-peak hours. Suppose too, that the customer uses 2 kWh/day on-peak and 18 kWh/day off-peak. That is, the PVs generate 20 kWh/day and the household consumes 20 kWh/day.

	PV supply	Demand
On-peak	10kWh	2kWh
Off-peak	10kWh	18kWh
Total	20kWh/day	20kWh/day

For a 30-day month in the summer, find the electric bill for this customer if the TOU rates of Table 5.2 apply.

Solution During the on-peak hours, the customer generates 10 kWh and uses 2 kWh, so there would be a credit of

$$\text{On-peak credits} = 8\ \text{kWh/day} \times \$0.19793/\text{kWh} \times 30\ \text{day/mo} = \$47.50$$

During the off-peak hours, the customer generates 10 kWh and uses 18 kWh, so the bill for those hours would be

$$\text{Off-peak bill} = 8\ \text{kWh/day} \times \$0.08514/\text{kWh} \times 30\ \text{day/mo} = \$20.43/\text{mo}$$

So the net bill for the month would be

$$\text{Net bill} = \$20.43 - \$47.50 = -\$27.07\text{mo}$$

That is, the utility would owe the customer \$27.07 for this month. Most likely in other months there will be actual bills against which this amount would be credited.

Notice that the bill would have been zero, instead of the \$27.07 credit, had this customer elected the standard rate schedule of Table 5.1 instead of the TOU rates.

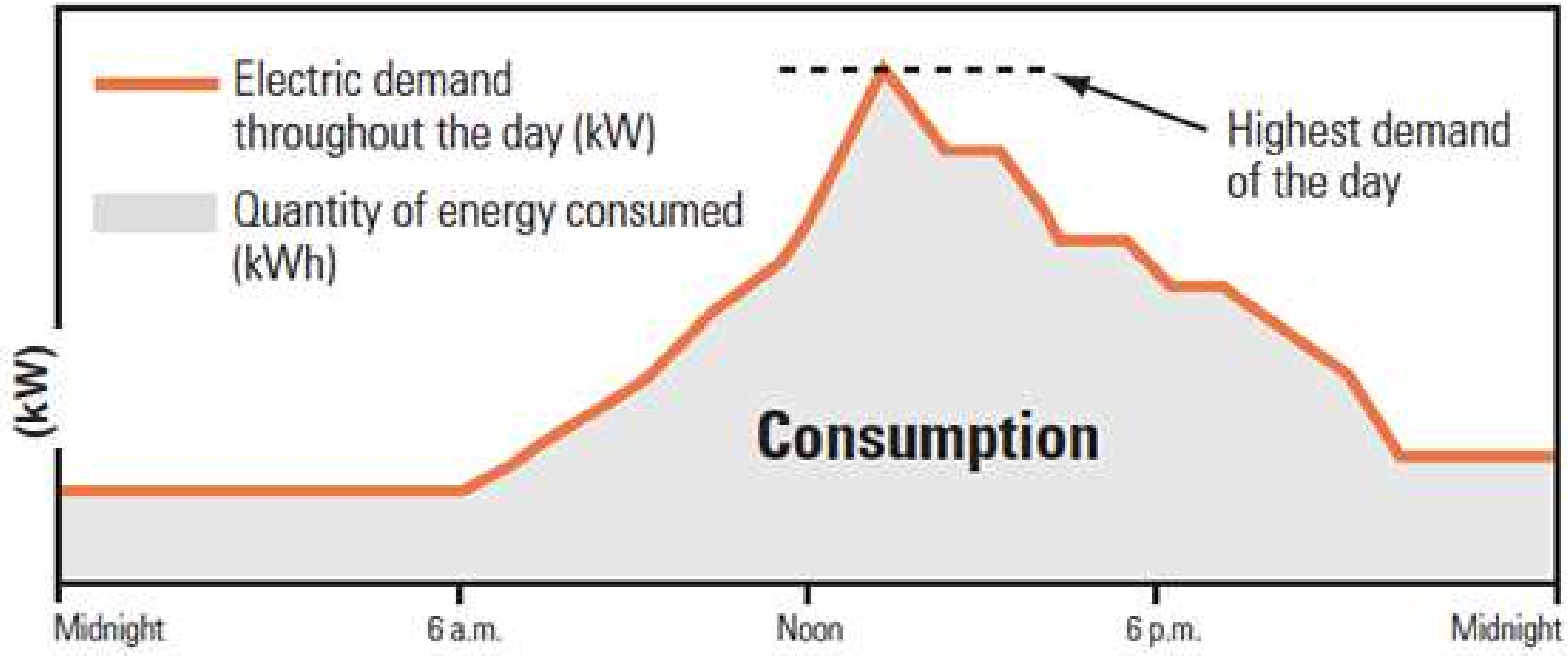
Demand Charges

- Along with fixed monthly fees, commercial electricity customers are typically billed for energy in two distinct ways:
    1. Consumption charges and
    2. Demand charges

- Consumption charges (also known as energy charges), are applicable to residential customers as well, are for the volume of electricity consumed, and are measured in kilowatt-hours (kWh).

- Demand charges, which are not usually applied to residential bills, are for the highest level of electricity demand during a billing period ("peak demand") and are measured in kilowatts (kW).

Consumption vs Demand charges



Demand charges

- Demand charges are designed as a way for utilities to recover some of the costs associated with providing sufficient electricity generation and distribution capacity to their customers.
- By basing a portion of a customer's electricity bill on their highest level of electricity demand, the utility is attempting to distribute more of the costs associated with building and maintaining the capacity of its power system to those who use it most.
- Commercial customers typically face demand charges ($/kW) based on their peak demand during each billing period.
- This peak demand is usually defined as the highest average electricity usage occurring within a defined time interval (often 15 minutes) during the billing period.
- For many commercial customers, demand charges can account for 30 to 70 percent of the total charges on a monthly electric bill.

Demand Charge Example

TABLE 5.3 Electricity Rate Structure Including Monthly Demand Charges

	Winter Oct–May	Summer June–Sept
Energy charges	\$0.0625/kWh	\$0.0732/kWh
Demand charges	\$7/mo-kW	\$9/mo-kW

Example 5.3 Impact of Demand Charges. During the summer, a small commercial building that uses 20,000 kWh per month has a peak demand of 100 kW.

a. Compute the monthly bill (ignoring fixed customer charges).

b. How much does the electricity cost for a 100-W computer that is used 6 h a day for 22 days in the month? The computer is turned on during the period when the peak demand is reached for the building. How much is that in ¢/kWh?

Solution

a. The monthly bill is made up of energy and demand charges:

$$\text{Energy charge} = 20{,}000\ \text{kWh} \times \$0.0732/\text{kWh} = \$1464/\text{mo}$$

$$\text{Demand charge} = 100\ \text{kW} \times \$9/\text{mo-kW} = \$900/\text{mo}$$

For a total of $\$1464 + \$900 = \$2364/\text{mo}$ (38% of which is demand)

b. The computer uses $0.10\ \text{kW} \times 6\ \text{h/d} \times 22\ \text{day/mo} = 13.2\ \text{kWh/mo}$

$$\text{Energy charge} = 13.2\ \text{kWh/mo} \times \$0.0732/\text{kWh} = \$0.97/\text{mo}$$

$$\text{Demand charge} = 0.10\ \text{kW} \times \$9/\text{mo-kW} = \$0.90/\text{mo}$$

$$\text{Total cost} = \$0.97 + \$0.90 = \$1.87/\text{mo}$$

On a per kilowatt-hour basis, the computer costs

$$\text{Electricity} = \frac{\$1.87/\text{mo}}{13.2\ \text{kWh/mo}} = \$0.142/\text{kWh}$$

Notice how the demand charge makes the apparent cost of electricity for the computer (14.2¢/kWh) nearly double the 7.32 ¢/kWh price of electric energy.

Demand Charges with a Ratchet Adjustment

- The revenue derived from demand charges that may only be monetarily significant for just one month of the year.
- This may not be sufficient for the utility to pay for the peaking power plant they had to build to supply that load.
- To address that problem, it is common to have a ratchet adjustment built into the demand charges.

  e.g. The demand charge for every month may be based on 80% of the annual peak demand.

Ratcheted Demand Charges - Example

Example 5.4 Impact of Ratcheted Demand Charges on an Efficiency Project. A customer's highest demand for power comes in August when it reaches 100 kW. The peak in every other month is less than 70 kW. A proposal to dim the lights for 3 h during each of the 22 workdays in August will reduce the August peak by 10 kW. The utility's energy charge is 8¢/kWh and its demand charge is $9/kW-mo with an 80% ratchet on the demand charges.

a. What is the current annual cost due to demand charges?
b. What annual savings in demand and energy charges will result from dimming the lights?
c. What is the equivalent savings expressed in ¢/kWh?

Solution

a. At \$9/kW-mo, the current demand charge in August will be

$$\text{August} = 100\ \text{kW} \times \$9/\text{kW-mo} = \$900$$

For the other 11 months, the minimum demand charge will be based on 80 kW, which is higher than the actual demand:

$$\text{Sept–July demand charge} = 0.8 \times 100\ \text{kW} \times \$9/\text{kW-mo} \times 11\ \text{mo} = \$7920$$

So the total annual demand charge will be

$$\text{Annual} = \$900 + \$7920 = \$8820$$

b. By reducing the August demand by 10 kW, the annual demand charges will now be

$$\text{August} = 90\ \text{kW} \times \$9/\text{kW-mo} = \$810$$

$$\text{Sept–July} = 0.8 \times 90\ \text{kW} \times \$9/\text{kW-mo} \times 11\ \text{mo} = \$7128$$

$$\text{Total annual demand charge} = \$810 + \$7128 = \$7938$$

$$\text{Annual demand savings} = \$8820 - \$7938 = \$882$$

$$\text{August energy savings} = 3\ \text{h/d} \times 10\ \text{kW} \times 22\ \text{days} \times \$0.08/\text{kWh}$$
$$= \$52.80$$
$$\text{Total Annual Savings} = \$882 + \$52.80 = \$934.80$$

Notice that the demand savings is 94.4% of the total savings!

c. Dimming the lights saved 3 h/d × 10 kW × 22 d = 660 kWh and \$934.80, which on a per kWh basis is

$$\text{Savings} = \frac{\$934.80}{660\ \text{kWh}} = \$1.42/\text{kWh}$$

In other words, the business saves \$1.42 for each kWh that it saves, which is about 18 times more than would be expected if just the \$0.08/kWh cost of energy is considered.

Load Factor

- The ratio of a customer's average power demand to its peak demand, called the load factor,
  - $Load\ factor\ (\%) = \frac{Average\ Power}{Peak\ Power} \times 100\%$
- It is a useful way for utilities to characterize the cost of providing power to that customer
- Example
- For example, a customer with a peak demand of 100 kW that uses 876,000 kWh/yr (8760 h/yr × 100 kW) would have an annual load factor of 100%.
- Another customer using the same 876,000 kWh/yr with a peak demand of 200 kW would have a load factor of 50%.

Impact of Load Factor on Electricity Costs

Example

Two customers each use 100,000 kWh/mo.

Customer A has a load factor of 15%

Customer B has a 60% load factor.

Using a rate structure with energy charges of $0.06/kWh and demand charges of $10/kW-mo, compare their monthly utility bills.

Solution. They both have the same energy costs: 100,000 kWh/mo × \$0.06/kWh = \$6000/mo

Using (5.1), the peak demand for A is

$$\text{Peak(A)} = \frac{100{,}000\ \text{kWh/mo}}{15\% \times 24\ \text{h/day} \times 30\ \text{day/mo}} \times 100\% = 925.9\ \text{kW}$$

which, at \$10/kW-mo, will incur demand charges of \$9259/mo.

The peak demand for B is

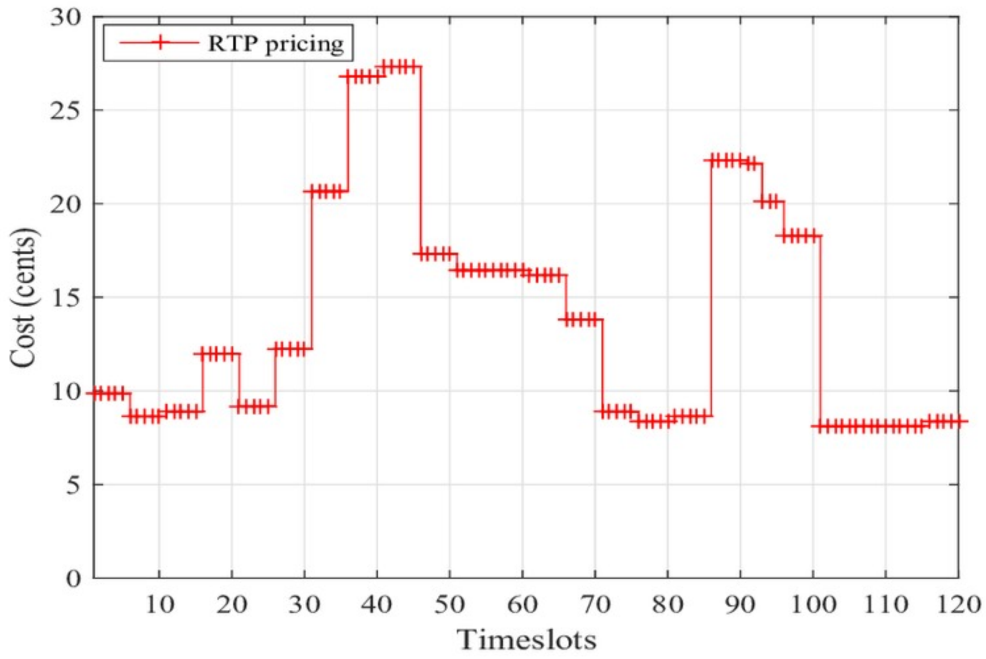
$$\text{Peak(B)} = \frac{100{,}000\ \text{kWh/mo}}{60\% \times 24\ \text{h/day} \times 30\ \text{day/mo}} \times 100\%$$

$$= 231.5\ \text{kW} \qquad \text{costing \$2315/mo}$$

The total monthly bill for A with the poor load factor is nearly twice as high as for B (\$15,259 for A and \$8315 for B).

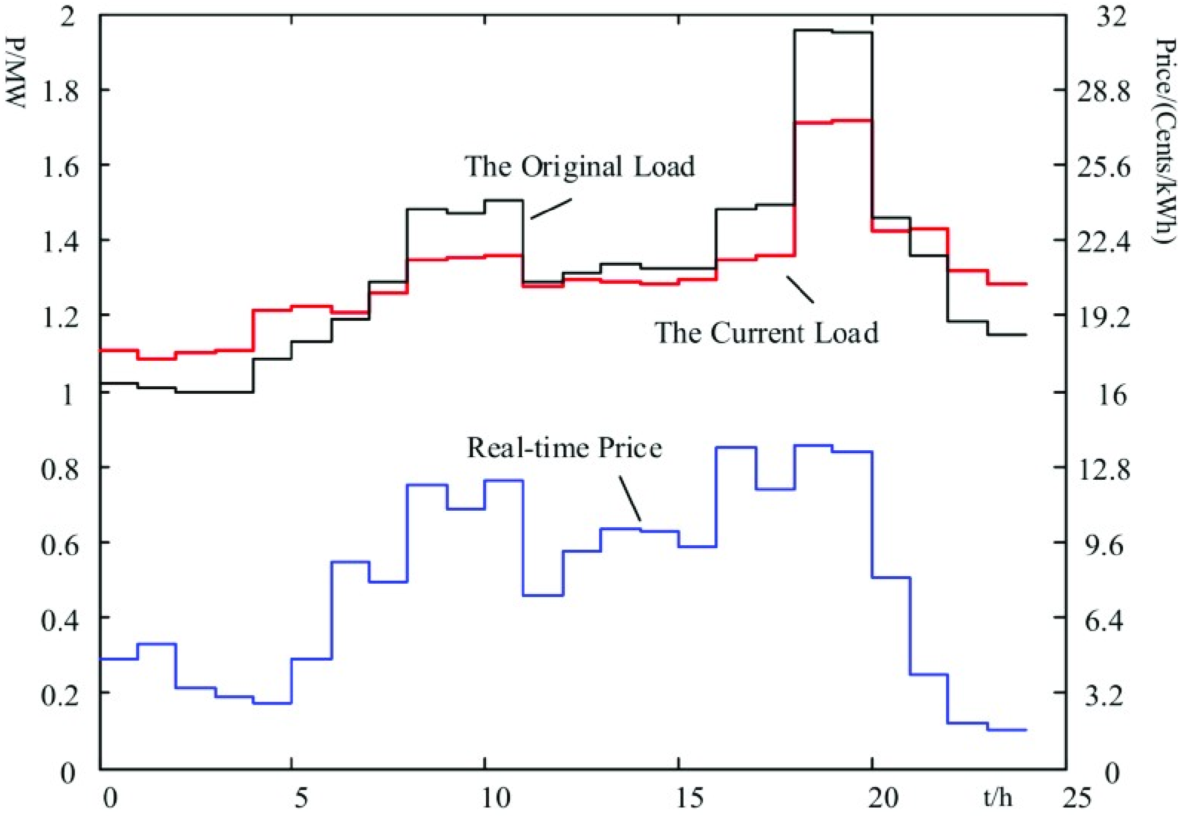
Real-Time Pricing (RTP)

- Time-of-use (TOU) rates are crude Differentiation of large blocks of time as Peak, partial-peak, off-peak.
- Real-time pricing (RTP) in which the true cost of energy is reflected in rates that change throughout the day, each and every day.



Real-Time Pricing (RTP) response

- When a customer knows the price of electricity in advance, they can implement appropriate measures to respond to high price.
- It is hoped that market forces will encourage the most efficient management of demand.



Energy Economics

- To test the economic viability of distributed generation and energy efficiency projects.

- The three cost components:
  1. capital cost of equipment,
  2. the operation and maintenance costs, and
  3. the fuel costs

must be combined in some manner so that a comparison may be made with the costs of not doing the project.

Methods of checking economic viability

- Simple Payback Period
- Initial (Simple) Rate-of-Return
- Net Present Value

Simple Payback Period

This is just the ratio of the extra first cost ΔP to the annual savings, S.

$$Simple\ payback = \frac{Extra\ first\ cost\ \Delta P\ (\$)}{Annual\ savings\ S(\$/yr)}$$

For example, an energy-efficient air conditioner that costs an extra $1000 and which saves $200/yr in electricity would have a simple payback of 5 years.

Simple Payback Period

- The easiest to understand of all economic measures
- One of the least convincing ways to present the economic advantages of a project.
- A very short payback period is demanded
- One of the most misleading measures since it doesn't include anything about the longevity of the system.

Initial (Simple) Rate-of-Return

The initial (or simple) rate of return is just the inverse of the simple payback period.

It is the ratio of the annual savings to the extra initial investment:

$$Initial\,(simple)\,rate\ of\ return$$

$$= \frac{Annual\ savings\ S\ (\$/yr)}{Extra\ first\ cost\ \Delta P\ (\$)}$$

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Initial (Simple) Rate-of-Return

- Just as the simple payback period makes an investment look worse than it is, the initial rate of return does the opposite and makes it look too good.
- Even though the initial rate of return may be misleading, it does often serve a useful function as a convenient "minimum threshold" indicator.

Net Present Value (NPV)

- One dollar 10 years from now is not as good as having one dollar in your pocket today.
- All future costs are converted to an equivalent *present value or present worth.*
- If you have amount *P* in your bank account today and earn annual interest at rate of *i*, then after *n* years, it will grow to:

$$F = P(1+i)^n$$

- This means an amount of *F* after *n* year is worth amount *P* today:

$$P = \frac{F}{(1+i)^n}$$

Discount Rate

- When converting a future value F into a present worth P, the interest term *i* is usually referred to as a discount rate *d*.

$$P = \frac{F}{(1+d)^n}$$

- To find the present value *P* of a stream of annual cash flows *A*, for *n* years into the future, with a discount rate *d*, we can introduce a conversion factor called the, *present value function* (PVF).

- $P = A.PVF(d,n)$

Present value function (PVF)

$$PVF(d,n) = \frac{1}{1+d} + \frac{1}{(1+d)^2} + \cdots + \frac{1}{(1+d)^n} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

Internal Rate of Return (IRR)

- IRR is the discount rate that makes the net present value of the energy investment equal to zero.
- Any project with an IRR greater than its cost of capital should be a profitable one.

NPV and IRR with Fuel Escalation

- The chances are that the cost of fuel in the future will be higher than it is today.
- Fuel price escalation factor (e) is used in the present worth analysis:

$$PVF(d,n) = \frac{1+e}{1+d} + \frac{(1+e)^2}{(1+d)^2} + \cdots + \frac{(1+e)^n}{(1+d)^n} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

- The fuel price escalation can be captured through the equivalent discount rate.

$$\frac{1+e}{1+d} = \frac{1}{1+d'} \text{ where } d' = \frac{d-e}{1+e}$$

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Example 5.7 Net Present Value of Premium Motor with Fuel Escalation. The premium motor in Example 5.6 costs an extra \$500 and saves \$192/yr at today's price of electricity. If electricity rises at an annual rate of 5%, find the net present value of the premium motor if the best alternative investment earns 10%.

Solution. Using (5.15), the equivalent discount rate with fuel escalation is

$$d' = \frac{d - e}{1 + e} = \frac{0.10 - 0.05}{1 + 0.05} = 0.04762$$

From (5.9), the present value function for 20 years of escalating savings is

$$\mathrm{PVF}(d', n) = \frac{(1 + d')^n - 1}{d'(1 + d')^n} = \frac{(1 + 04762)^{20} - 1}{0.04762(1 + 0.04762)^{20}} = 12.717 \text{ yr}$$

From (5.10), the net present value is

$$\mathrm{NPV} = \Delta A \times \mathrm{PVF}(d', n) - \Delta P \quad = \$192/\text{yr} \times 12.717 \text{ yr} - \$500 = \$1942$$

(Without fuel escalation, the net present value of the premium motor was only \$1135.)

Annualizing the Investment

- Extra capital required for an energy investment will be borrowed from a lending company.
- The extra capital cost is converted into a series of n equal annual payments (A) that eventually pay off the loan(P) with interest (i).

$$A = P \times CRF(i, n)$$

$$CRF(i, n) = Capital\ recovery\ factor(yr^{-1}) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$CRF(i, n)\ per\ month = \frac{(i/12)[1+(i/12)])^{12n}}{[1+(i/12)])^{12n} - 1}$$

Levelized Costs

- The cost of a power plant has two key components - an up-front fixed cost to build the plant plus an assortment of costs that will be incurred in the future.
- In the usual approach to cost estimation, a present value calculation is first performed to find an equivalent initial cost, and then that amount is spread out into a uniform series of annual costs.
  - Levelized annual costs = $A_0[\mathrm{PVF}(d', n) \cdot \mathrm{CRF}(d, n)]$
- The ratio of the equivalent annual cost ($/yr) to the annual electricity generated (kWh/year) is called the levelized cost of electricity (LCOE).

Levelizing Factor

$$\text{Levelizing factor (LF)} = \left[\frac{(1+d')^n - 1}{d'(1+d')^n}\right] \cdot \left[\frac{d(1+d)^n}{(1+d)^n - 1}\right]$$

Price of Electricity from a Wind Farm - Example

A wind farm project has 40 1500-kW turbines with 64-m blades. Capital costs are $60 million and the levelized O&M cost is $1.8 million/yr. The project will be financed with a $45 million, 20-yr loan at 7% plus an equity investment of $15 million that needs a 15% return. Turbines are exposed to Rayleigh winds averaging 8.5 m/s.

What levelized price would the electricity have to sell for to make the project viable?

Solution

$$\text{CF} = 0.087\overline{V}\ (\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} = 0.087 \times 8.5 - \frac{1500}{64^2} = 0.373$$

For 40 such turbines, the annual electrical production will be

$$\begin{aligned}\text{Annual energy} &= 40 \text{ turbines} \times 1500 \text{ kW} \times 8760 \text{ h/yr} \times 0.373 \\ &= 196 \times 10^6 \text{ kWh/yr}\end{aligned}$$

The debt payments will be

$$\begin{aligned}A = P \cdot \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] &= \$45{,}000{,}000 \cdot \left[\frac{0.07(1+0.07)^{20}}{(1+0.07)^{20} - 1}\right] \\ &= \$4.24 \times 10^6/\text{yr}\end{aligned}$$

Solution

The annual return on equity needs to be

$$\text{Equity} = 0.15/\text{yr} \times \$15{,}000{,}000 = \$2.25 \times 10^6/\text{yr}$$

The levelized O&M cost is $1.8 million, so the total for O&M, debt, and equity is

$$\text{Annual cost} = \$(4.24 + 2.25 + 1.8) \times 10^6 = \$8.29 \times 10^6/\text{yr}$$

The levelized price at which electricity needs to be sold is therefore

$$\text{Selling price} = \frac{\$8.29 \times 10^6/\text{yr}}{196 \times 10^6\ \text{kWh/yr}} = \$0.0423 = 4.23¢/\text{kWh}$$

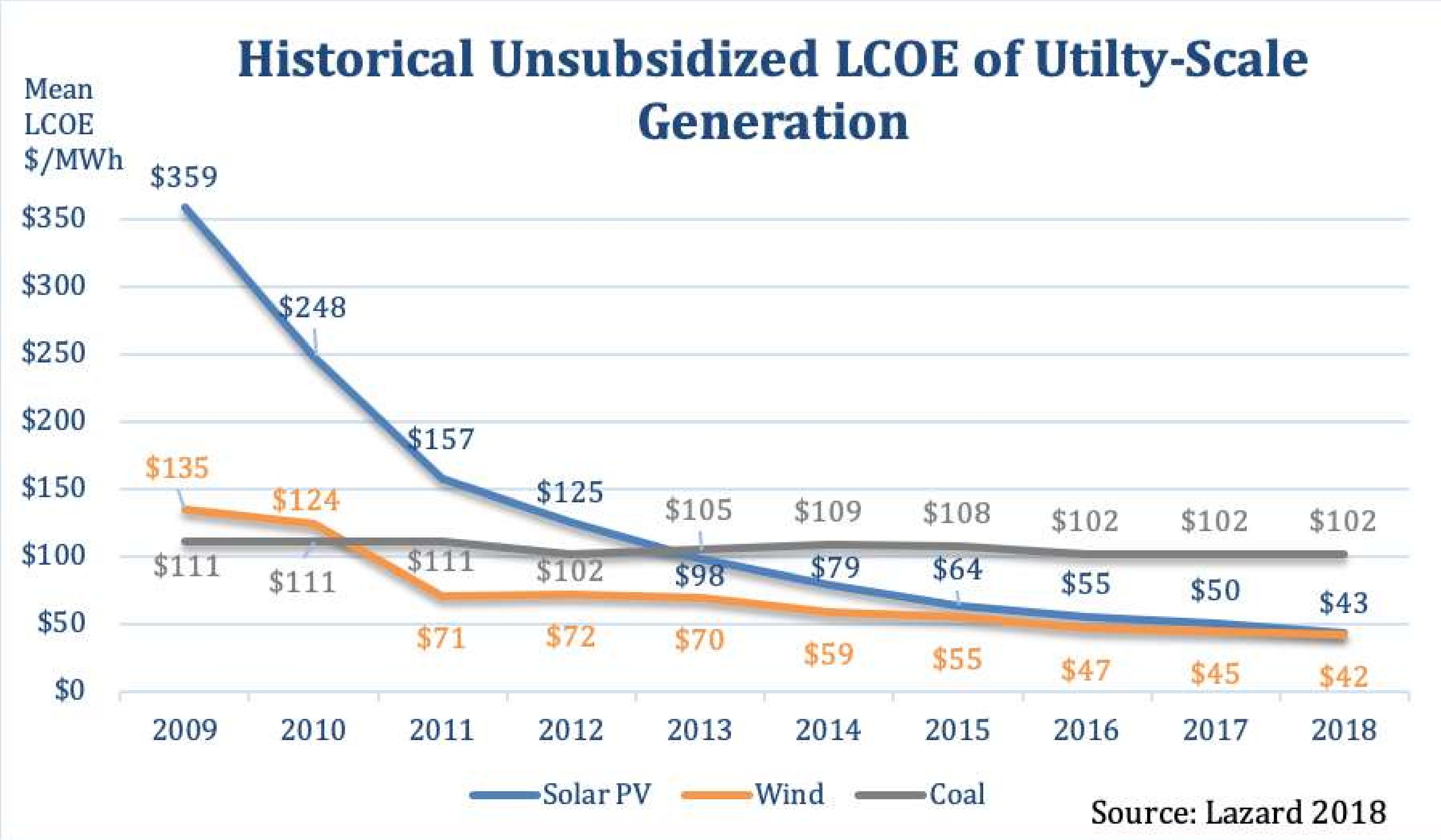
LCOE

- The levelized cost of energy (LCOE) is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis.
- It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime.
- The LCOE can also be regarded as the average minimum price at which electricity must be sold in order to break even over the lifetime of the project.

Limitations of LCOE

- LCOE ignores time effects associated with matching production to demand.

- This happens at two levels:
  1. Dispatchability, the ability of a generating system to come online, go offline, or ramp up or down, quickly as demand swings.
  2. The extent to which the availability profile matches or conflicts with the market demand profile.


Historical Unsubsidized LCOE of Utilty-Scale Generation
Mean LCOE $/MWh
$350
$300
$250
$200
$150
$100
$50
$0
$359
$248
$157
$125
$98
$79
$64
$55
$50
$43
$135
$124
$71
$72
$70
$59
$55
$47
$45
$42
$111
$111
$111
$102
$105
$109
$108
$102
$102
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2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Solar PV
Wind
Coal
Source: Lazard 2018