Resources – Renewables

Outline

- Hydro
- Solar

Based on

Potential Energy

- Dropping from a higher altitude, water loses potential energy, which is proportional to mass and weight.
  - If mass in kg; height of drop in meters; gravitational acceleration constant in \( g = 9.8 \, \text{m/s}^2 \), then multiply these to obtain potential energy in Joules.
  - Water gains potential energy when it evaporates with the heat coming from the sun.
  - Water at high elevations can be thought as a solar energy storage mechanism.
- What is the fuel cost at a hydroelectric dam? Zero
- Head is the term in the hydroelectric industry used for the height of the drop.
- Potential energy captured by \( m \) kgs at \( h \) (head) is \( m \, g \, h \)

\[ m = 1000 \, \text{kg} \] of water at \( h = 100 \, \text{m} \) high has potential energy of 1 million Joules.

\[ 1 \, \text{million Joules} = 1,000,000 \, \text{kg} \, \text{m}^2/\text{s}^2 = 1,000 \, \text{kg} \times 10 \, \text{m/s}^2 \times 100 \, \text{m} \]

- 1 Joule/s = 1 Watt; So 1 million Joules is 1 MWs.
- Example: Hoover Dam generates 2080 MW with 17 turbines and head of about 200 m. Consider a turbine with 100 MW. How much water should go through this turbine per second to generate 100 MW?

\[ 100,000,000 = m \times 10 \times 200 \quad \text{so} \quad m = 50,000 \, \text{kg} = 50 \, \text{tons of water per second}. \]

- Example: Three Gorges Dam has 750 MW turbines and similar head, how much water should pass through each 750 MW turbine?
Hydroelectric Dams

A hydroelectric plant includes

- Dam traps the water to build a reservoir.
- Reservoir stores the water at a higher altitude and is connected to the surface of the water behind (downstream) the dam through pipes.
- Pipes (penstock) bring the water down in a controlled fashion to the powerhouse.
- Powerhouse includes the turbines rotated by falling water and electricity generated in the powerhouse is transmitted to the electrical substation.
- Electrical substation increases the voltage for long-distance transmission.
Three Types of Hydroelectric Dams

◆ **Impoundment**: Reservoir fills naturally with the water flowing from upstream.
  – Advantage: Reduced seasonality of water flow. Flood reduction; agricultural irrigation.
  – Disadvantage: Big footprint. Existing villages and natural life go underwater. Large lakes can change ecology and can create microclimates.

◆ **Diversion**: No reservoir. River (a stream thereof) flows through penstock.
  – Advantages: Low cost as no dam is built. It has limited/no footprint.
  – Disadvantage: Exposure to seasonality of water flow.
    » Seasonality is less in tropical or subtropical climates: Hawaii, Central America or Brazil.

◆ **Pumped storage**: Reservoir is filled with recycled water.
  – Think of a two (artificial) lakes at different altitudes.
  – Water flows from the upper to the lower to generate electricity.
  – Electricity is used to pump water up from the lower to fill the upper.
  – Under ideal conditions, no gain or loss.
  – In reality, friction causes losses during conversions.
  – This is viable as pumping happens when electricity is cheap (night) while generation happens when electricity is expensive (day). Demand for electricity is low in the night and so is its price.

The naturally pumped storage allows Hydro-Québec to obtain 99% of its electricity from emission-free renewables. “Some 80% of the Quebec demand is along the St. Lawrence River, but our generating capacity is 1,000 or more miles away in the province’s hydropower. Our reservoir is about 170 gigawatt-hours (170,000 MWH) of capacity, which is a huge battery. Goals for energy storage include regulating wind and solar ….” according to J. Jessop, Hydro-Quebec Research Institute.

**Taum Sauk Pumped Storage: Heart of Ozarks**

- **Taum Sauk** is a pumped storage reservoir close to Taum Sauk mountain (highest peak in Missouri), a part of Ozark Mountain Range.
- **It has two reservoirs:**
  - Upper reservoir is on Proffit mountain.
  - Lower reservoir is on the East fork of Black river.
- Upper reservoir has 30 meter walls and holds 5.7 million cubic meter of water 240 metres above the power turbines.
- Upper reservoir is filled from the lower reservoir during nights through a 2,100 metre tunnel.

The upper reservoir stores thousands of megawatt hour energy as potential energy of the water.

- Dec 15, 2005, the northwest wall overtopped by water and partially collapsed.
  - Suddenly 6 meter wave of water flowed down the mountain, clearing out the thick forest and a house. Luckily, no fatalities.
  - FERC fined the owner AmerEn for $15 million.
  - Northwest wall was rebuilt and the reservoir is operational since the 2010s.
Sizes and Technologies

- Sizes according to Department of Energy
  - Micro: Less than 0.1 MW.
  - Small: Between 0.1 and 30 MW.
  - Large: More than 30 MW.

- Types of Turbines
  - Pelton Turbine: Radial in and out
  - Francis Turbine: Radial in; Axial out
  - Kaplan Turbine: Immersed into water
Environmental Issues

◆ Fish mortality
  – When fish enter the penstock and reach the turbines, they may die.
  – Single pass mortality rate in most existing turbines is 5-10%.
  – New turbine designs can reduce it down to 2%.
    » Screw Turbine. Water rotates the turbine as it flows downwards.

◆ Water quality standards
  – Dissolved oxygen (DO) in the downstream water can be made more than 6 mg per liter.
  – Dissolved oxygen is more in freshwaters and in Springs.
  – Texas Commission on Environmental Quality
    » DO mean 6 mg/L is exceptional; 5 is high; 4 is intermediate; 3 is limited; 2 is minimal.
    » Trinity River Basin Segments
      ◆ Lewisville Lake, Grapevine Lake, White Rock Lake all have 5 mg/L.
    » San Jacinto River Basin Segments
      ◆ Houston Ship Channel Tidal has 2 mg/L and Buffalo Bayou Tidal has 1 mg/L.

◆ Carbon dioxide emissions
  – Nothing is burnt – no emissions
Hydropower Capacity and Expansion

- US installed hydropower capacity is 100,000 MW. This is the second after China’s 149,000 MW according to an EIA report in 2010.
  - 6.5% of domestic energy generation in US. 16.9% in China. 58.7% in Canada. 98.5% in Norway.
- FERC estimates an additional 73,200 MW capacity by taking only engineering and financial feasibility into account. That is 73,200 MW is the maximum possible capacity.
- DoE refined FERC’s 73,200 MW estimate by also considering environmental and legal constraints to arrive at 30,000 MW.
  - 57% of this capacity increase can be from generating electricity at existing dams that do not currently generate.
  - 14% is by increasing the capacity / efficiency / utilization of the existing hydropower plants.
  - 28% by building new dams.

- Why extra capacity not brought into line immediately?
    - Pre-application activity should start 5 years before the expected date of license issuance.
  - Original licenses are issued for 50 years; Relicences are for 30-40 years. Periods are long enough for the owner to recover financial investment.
  - Owners of capacity in MW: 50% Federal institutions; 24% Private utility; 22% Non-federal public (e.g., municipalities).
  - Owners of dams in numbers: 31% Private utility; 27% Private non-utility (e.g., Hawaiian Commercial and Sugar Company); 24% Non-federal public; 9% Industrial; 7% Federal institutions.

Hydropower Future

- Hydroelectric plants in US,
  - Licensing for smaller plants (<5 MW) is simpler and exemptions are possible.
  - Turbines using naturally dropping water are easier to license.
  - Smart and extensive electricity grids can make small projects viable.
  - A greenhouse gas reduction policy can encourage hydropower plants.
  - Fish-friendly turbines can ease environmental objections.
  - Greater efficiency from advanced turbines.
  - Increased appreciation of stability of hydroelectric power (as opposed to solar/wind power) helps hydro projects.

- Hydroelectric plants in the rest of the world,
  - Canada, Brazil, China have high hydroelectric power capacity and potential (mountains with rivers).
  - China has acquired/developed technology through Three Gorges Dam
    - 22,500 MW capacity with Francis turbines
    - Relocation of towns, Ground slides, Fault line can be triggered by altering water levels in the reservoir.

Hydropower Future: Tidal and Wave Power

Tidal power

◆ Tides are created mostly by moon’s gravity, and somewhat by rotation of earth and sun’s gravity.
◆ Tides are predictable at each location
◆ They differ across locations.
◆ A tidal dam is efficient when the difference between high and low tides is substantial.

Bay of Fundy, Eastern Canada – Northern Maine, difference > 40 feet.
Cook Inlet in Alaska; Sea of Okhotsk on Eastern Russian Seaboard.
◆ Built in 1960, La Rance tidal dam in Northwest France can produce 240 MW with 24 turbines.
◆ Severn Estuary Dam between England and Wales; Considered by British government, see www.corlanhafren.co.uk.

Wave Power

◆ Waves are created by winds, a turbine will not work.
◆ Instead lay a snake like tube made up of about 5 segments.
◆ Segments are allowed to rotate with respect to each other at the hinges.
◆ Rotational energy at the hinges can be captured with pistons.
◆ A snake is laid down, west coast of Orkney Island, Scotland in Oct 2010. This is a test by the European Marine Energy Center.
Solar Energy

- Solar energy in the siege of Syracuse, Sicily ≈ 214-212 BC. Syracuse was a Hellenistic city and was attacked by Romans.
- According to a legend, during the siege, Archimedes-designed mirrors burned Roman ships. At the end, Rome conquered the city and 75+ year old Archimedes was killed by Roman soldiers.
Nuclear energy → Electromagnetic Energy → Solar Energy

- Helium fusion reactions take place in the sun and mass (4 mega tons / second) is converted into energy.
- Sun’s temperature at the center 15,000,000 K (kelvin) on the surface 6000 K (5727 celsius).

- A heated up a metal (substance that does not burn) becomes first red and then yellow. It emits light.
- An ideal model for sun’s light emission is blackbody radiation. A blackbody does not reflect any light but can emit its own. A blackbody does not appear black to eye.
- Depending on its temperature $T$, a black body emits power $P(\lambda, T)$ at different wavelengths $\lambda$.

- The total power emitted is the area under $P(\lambda, T)$ Planck curve. Higher temperature objects emit more power but at lower wavelengths.
- Units of total power is watts per squaremeter; as stredian is a nuisance unit.
- An approximate formula for $P(\lambda, T)$ is offered by Planck.
Solar Power on Atmosphere and Surface

- Light is neither a wave nor a particle; it is both. This is known as wave-particle duality in quantum physics.
- Light has energy proportional to its frequency by Planck equation.
- Take the blackbody radiation Planck curve at 5777 K from the previous page and get rid of strian when moving from the Y-axis of the previous page to the Y-axis below.

The radiation that falls on the earth outside atmosphere is more than the radiation on the surface.
- Atmosphere (ozone, oxygen, water, carbondioxide) absorbs particular wavelengths of emission. E.g., Ozone $O_3$ absorbs short wavelength (high energy) emissions. Lack of ozone $\Rightarrow$ High energy emissions $\Rightarrow$ Skin cancer.
- The power that reaches the earth’s atmosphere is approximately the area of the triangle above with base 1750-250 and height 1.75. The area is 1312.5 $watt/m^2$. The empirical value is 1361 $watt/m^2$. 
Solar Power Accounting for Zenith Angle

- Solar power provides ~ 1360 W/m² outside the earth’s atmosphere. This is also called AM0 irradiance.
- It provides less after passing through the atmosphere. When the sun is falling directly, air mass (AM) = 1.

\[
AM = \frac{1}{\cos(Zenith \ Angle)}
\]

- Half of 1360 W/m² reaches solar panels. The rest is reflected back to space or absorbed by the atmosphere.
- When the zenith angle is wider, the light must travel longer in the atmosphere and drops more of its energy at the atmospheric particles.
- AM1.5 irradiance is generally about 827 W/m².
- Industry rounds AM1.5 up to 1000 W/m².
- Earth wide average solar power input is 650 W/m².
Solar Power Accounting for Night and Clouds

- AM1.5’s 1 kW/m² (≈1,000 W/m²) is available during the day when the sun is visible.

Average daily 4.7 kWh/m²
Average annual 1715.5 kWh/m²
based on only day 1 and 2
Solar Power Area Requirement

- Overton, North Texas reaches maximum of about 6 kW/m² in August and minimum of about 2 kW/m² in December. Texas solar radiation database is [www.me.utexas.edu/~solarlab](http://www.me.utexas.edu/~solarlab).

- Southwest US receives more solar energy about 6 kW/m². Optimistically suppose sun is out 12 hours per day and 30% conversion efficiency so we can obtain 0.9 kW/m² of electricity at every hour.

- How many m² required to generate 350,000 kW (capacity of the solar plant in the Mojave desert)?
  - 350,000/0.9 = 388,888 m² which can be made up by a 623 metre x 623 metre square. A (American) football field is 4,500 m². About 90 football fields are needed.
  - Where to find such a large deserted land? In a desert!

- Total US generation capacity was 1,000,000,000 kW in 2007, which requires about 1,100,000,000 square meters = 250,000 football fields.
Roofs for Solar Power at UTD and around

- In 2013, UTD installs 220 kilo watt solar panels on the new Parking Structure, see the photo below. With this, UTD was able to participate in a Solar Program funded by Oncor and qualified to receive $203,722.
- UTD also qualified for another $98,371 in incentives during 2012 for efficient chiller installations and by constructing buildings that are more efficient than the code requirement.
- This brought the total incentive in 2013 to $302,093.

UTD’s Energy Revolving Fund reinvests these incentives in energy efficiency projects on campus. Savings from the projects refill the fund.

- Utility companies are required to invest in energy efficiencies in their service areas.
  - Oncor runs the “Take a Load off Texas” project, which funded $62 million in 2013.
  - CenterPoint invested $42 million in projects in 2013.

Harvesting Solar Power

- Sun’s energy can be harvested as **thermal solar power** and as **photovoltaic solar power**.
Thermal Solar Power

- Thermal solar power capacity of 70,000 MW dwarfed photovoltaic capacity of 1,100 MW in 2001.
  - Capacity in China 22.4 GW; US 17.5 GW; Japan 8.4 GW; Turkey 5.7 GW (receives 1400-2000 W/m²); Germany 3 GW.
- Direct use: Solar power used to heat water that later is used for heating buildings or to serve hot water needs.
- Indirect Use to generate Electricity (Concentrated Solar Power):
  - Collector absorbs the solar heat and passes to the water as it passes through it towards the storage tank.
  - Storage tank keeps the water hot and insulated. A secondary power source (electric or gas) can be used.
  - Hot water is used to generate steam for electricity turbines.
  - Collectors: Parabolic troughs (convex mirrors), Fresnel concentrator (flat mirrors), dish stirling (dish shaped mirror).
  - Heat transfer agent:
    » Water, which can be hard to come by in a desert.
    » Synthetic oil heated upto 735 F by convex mirrors, Mojave Desert, CA.
    » Molten salt heated upto 1050 F in a tower by Sunlight tracking mirrors. When power is needed molten-salt flows through a heat exchanger and cools down. Salt’s temperature drops at least down to 550 F, it has to remain molten.

Photovoltaic Solar Power:

Excited Electron’s Excursion from Valence to Conduction Band

Photovoltaic effect: Emission of electrons by materials exposed to light.

- Each electron resides in its regular orbit (its valence band) around the nucleus.
- While residing in its valence band, an electron has a certain amount of energy.
- Energy of an electron increase upon receiving photovoltaic energy (through a light photon).
- A rise in an electron’s energy,
  - If small, warms up the material.
  - If large, moves an electron from its valence band to the conduction band.
- Conduction band is further away from the nucleus and accommodates electrons that are ready to break away from their nucleus.
- If an electron in the conduction band is not directed through a circuit to come out away from its nucleus, it can drop back to its valence band.
  - In the process of falling back, the electron emits light: Fluorescent lamps excite gas electrons in the lamp with electricity. The electrons go up to their conduction band, fall back to their valence band and emit light.

\[
\text{Conduction band - Valence band} = \text{InSb, Indium Antimonide, crystal of Indium and Antimony.}
\]

\[
\text{Narrow band-gap semiconductor used in infrared detectors.}
\]

\[
\text{InAs, Indium Arsenide, crystal of Indium and Arsenide.}
\]

\[
\text{Ge, Germanium}
\]

\[
\text{GaSb, Gallium Antimonide, crystal of Gallium and Antimony.}
\]

\[
\text{Si, Silicone, crystal.}
\]

\[
\text{InP, Indium Phosphide, crystal of Indium and Phosphorus.}
\]

\[
\text{GaAs, Gallium Arsenide, crystal of Gallium and Arsenide.}
\]

\[
\text{Ga\textsubscript{x}Al\textsubscript{1-x}As, Gallium Aluminum Arsenide. Wide band-gap semiconductor.}
\]
Excitable Semiconductors to Harvest Photovoltaic Solar Power

Silicone has 14 electrons; 10 of them are stable in lower orbits; 4 (valence electrons) are in the external orbit.

Photovoltaic cells (PV) have two layers (as your pizza)
- n-layer is rich in electrons so it is negatively charged.
- p-layer is deprived of electron so it is positively charged.

As cheese topping in your pizza does not go into the crust, electrons do not naturally move to p-layer in an n-p two-layer semiconductor.
- Light brings electrons to a valance band of an n-layer. A circuit takes them to the p-layer and finally returns to n-layer.

Energy level to excite electrons depend on the composition of n-layer. Multiple n-layers (as multiple topping pizza) can catch different wavelengths and increase efficiency. Toppings are: Al, Ga, As, Ge, Si and their n- and p-layers.
Efficiently Capturing Solar Energy is matching the wavelengths of solar radiation with the wavelengths (energy) of valence band gaps by using appropriate mix of semiconductors.
Active research in developing new photovoltaic cells by using materials (Gallium, Arsenide) other than silicon and by using multiple layers (junctions). The highest solar-to-electricity conversion efficiency at the time of writing this document is 46%. This is higher than coal-to-electricity efficiency. Such high efficiency cells are not produced at industrial scale yet.
Industry: Photovoltaic Cells Types & Production

- Efficiency of converting solar energy to electric energy can range from
  - 7-13%: Thin-layer PV cells deposited on plastic (glass or steel).
  - 14%: Low-end polysilicon
  - 15-18%: High-end polysilicon made up of cleaner more pure silicon wafers.
  - 30%+: Gallium Arsenide PV cells used in the space program.

- Silicon wafers used in PV cells are as thin as 200 microns $10^{-6}$ meters and about 15-20 square centimeters.

- A PV cell is the building block producing about 1-2 watts. It is assembled into modules and arrays with serial connections.

- Global production of polysilicon is 69,000 tons in 2009.
  - Chinese production is 20,000 tons.
  - Half of this came from a single company: GCL Poly.
  - Polysilicon plant should have more than 5,000 tons of annual capacity to be competitive. A 10,000-ton plant can cost about $1 billion.
  - GCL Poly managers believe that the price should be about $28/kg others suggest higher prices.
  - US has competitive edge on thin-film PV production. Chinese firms Yingli and Trina are closing the gap.

Source: http://science.nasa.gov

Germany, Spain and USA are the first three in terms of leading installed capacity.

Governments offer incentives to consumers to adopt solar energy.
- In a FiT (Feed-in-Rate) contract a government pays consumers to reduce the gap between solar and conventional energy for extended period of time (20 years in Germany).
- Germany introduced FiT subsidies in 2000 and has been reducing them.
- Spain introduced FiT subsidies in 2007 at about €0.45/kWh and reduced it by 35% in 2008 and also by 30% in 2010. Consequently, polysilicon price collapsed from its heights of $450/kg.
Government Policies: Production and Consumption Assistance

- No production and no consumption assistance
  - Solar is not cost-competitive without assistance.
  - Upstream (Production) companies: Consolidate or withdraw.
  - Midstream companies: Fierce competition can lead to acquisitions of midstream companies by production companies.
  - Downstream companies: Find non-traditional customers such as municipal power companies, public utilities, residential users. Remove restrictions on widespread use such as limitations on rooftop installations in residential areas.

- Production assistance but no consumption assistance
  - Production grows, upstream companies benefit
  - Midstream companies want to sell in the international markets
  - China’s experience
    - Solyndra case in US: Failure to pay $535 million federally guaranteed loans.

- No production but consumption assistance
  - All benefit from higher demand.
  - Upstream companies may want to stop import boom
    - Use domestic content requirement as in Ontario’s to qualify for FiT.
  - Downstream companies should not be addicted to consumption assistance
    - Expand demand: Net-zero affordable homes in Arizona, California, Colorado, Nevada
  - Spain’s experience

- Both production and consumption assistance
  - Both may be unnecessary
Economics of Solar Power
Consumer’s Perspective

◆ A 2000 square foot home needs approximately 2000 W.
◆ The installation cost of panels to generate 2000 W is about $16,000. The latest gains in efficiency is puling the cost down.
  – The cost can be less in Texas because solar energy density is higher but also Texas houses are larger.
◆ A typical consumption assistance can pay for 50% of this cost so the consumer is left with $8,000.
◆ The total energy generated by these panels: 100,000 kW – hour = 2 * 5.5 * 365 * 25
  – 2 kW per hour.
  – 5.5 hours per day: accounting for clouds, sun at the horizon twice during the day.
  – 365 days per year.
  – 25 years of lifetime for panels.
◆ If the retail price of electric is $0.08 per kW-hour, the saving over panels life time is $8,000.
◆ Without 50% consumption assistance, consumers will not install panels.

◆ Time-of-day electric pricing advocates for charging higher during the day when the demand is higher than during the night when the demand is lower.
◆ If the retail price of electricity is $0.16 per kW-hour during the day when the panel is generating electricity, the saving over panels life time is $16,000.
◆ Without a consumption assistance but with time-of-day electric pricing, consumers will install panels.
◆ Who offers time-of-day electric pricing in zip code 75080 in March 2012?
  ◆ Go to [http://powertochoose.org](http://powertochoose.org), enter zip code, pick variable rate, companies include:
Summary – Renewable

- Hydro
- Solar