Intro to Electricity

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What Makes Electricity Interesting

- We somehow start with a fuel (Counting wind, geothermal and sunlight in this).
- Transport it from where we found it to a generating facility.
- Turn it into electricity losing some energy as heat.
- Run it along long wires to where people want to use it, losing yet more energy.
- From there send it out to every small location (losing more), and
- Because electricity is not *easily* stored, adjust the rate at which we generate electricity moment-by-moment to make sure there is just enough.

This is a logistical miracle.

Basic Units

- $Watts = AmpsVolts$ first thing everyone learns.
  - Pro tip on units, if it is someones name, capitalize it.
  - Volt is analogous to height.
  - Amp is analogous to a weight.
  - Watt is what it happens when that weight is dropped from that height.
  - DC is easy; AC is “complex”
- AC because it is a wave, has a few more components.
  - Real Power, measured in W, it is what does the work.
  - Reactive power, measured in volt-amps (var),“r” tells you it is reactive, is what pushes the electricity around.
  - Apparent Power, is in volt-amps too (VA) is when you add the two together in a vector sense.
  - Power Factor is the Real(W)/Apparent(VA).

What?

Caveat IANAE and I will do thing like call current amps and the like. Also, this is the simple, single phase, view with lots of simplifications. Reality is for engineers.

- The alternating part of AC is what causes the complication.
  - You can talk about instantaneous power but
  - Tend to talk about average power.
- With a resistive load, think light bulb, amps and volts are in sync
- Inductors and Capacitors throw amps and volts out of sync
  - Capacitors store energy in electric fields. Think a very burst battery.
    - Amps peak *before* volts
  - Inductors store energy in magnetic fields. Think about an electromagnet in a motor.
    - Amps peak *after* volts

Picture for this

AC Power to a Resistive Load

AC Power to a Inductive Load

AC Power to a Capacitive Load

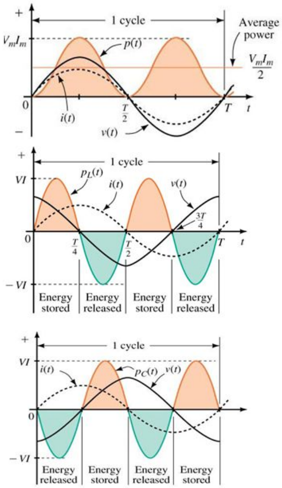


Figure 1:

Power Factor

- Measure it
  - Henrys are the unit for inductance/capacitance and engineers use that in calculations
  - There are also power factor meters
  - You can also check out the difference between amps and volt on oscilloscope.
- Low numbers mean the utility needs to generate more power than customer uses.
  - Can happen with low load, like a motor barely moving, but you still need the electromagnet
  - Common solution is to install capacitors somewhere to cancel out the inductor

Why do we care about reactive power and power factors?

- Engineers have to design systems to accommodate not just the real, but real plus reactive, i.e., apparent power.
- Reactive power has to be generated.
- Not residential tariffs, but commercial and industrial tariffs charge for reactive power or have penalties for low power factors.

kW vs kWh

- kW is instantaneous and called power
- kWh is the integral over time and called energy.
- 100 W light bulb uses 100 Wh $=$ 1/10 kWh per hour
- Get used to flipping between 1,000,000,000 W $=$ 1,000,000 kW $=$ 1,000 MW $=$ 1 GW

Lets Generate Some Electricity

- Turbine – spin something in a magnetic field to induce a current.
- Lots of ways to spin a turbine
  - Coal, grind it up, burn it, make steam, use steam to spin the turbine.
  - Nuclear, use the heat to make steam, use steam to spin a turbine.
  - Biomass, burn stuff to . . .
  - Gas, burn it to spin a turbine . . .
  - Fuel Oil or Diesel
  - Solar thermal, use the sun to make steam . . .
  - Water, falling water hits a turbine and spins it
  - Wind, spin a turbine
  - etc.
- Or don't spin a turbine and go for photo-voltaic, PV.

Characteristics

- Nameplate, fully loaded under ideal conditions (MW)
- Ramp rate, how fast power (MW) can change MW/min
  - Not always constant, can differ by capacity factor (fraction of nameplate)
  - Not always symmetric, up different from down.
  - Used to follow the load.
- Heat rate, BTU in/ BTU out, or BTU per kWh, only used for generation that uses a fuel.
  - It is impossible but 1 kW = 3412 BTU.
  - Not so streigt forward for renewables (`http://www.eia.gov/totalenergy/data/annual/pdf/sec17.pdf`)
  - Recent average from EIA, `https://www.eia.gov/electricity/annual/html/epa_08_01.html`

Coal from the outside

Source: http://appvoices.org/images/uploads/2012/02/Asheville-coal-plant-e1432059203783.jpg

Coal on the inside

- Pulverize the coal, picture something that can do 20 Tons/hr
- Blow it into combustion chamber to burn
- Steam turns turbine, etc. `https://youtu.be/IdPTuwKEfmA`
- Clean up
  - NOx with ammonia common but plenty of others
  - Recover fly ash and sell it, great for concrete.
  - SOx, Mercury and other. BTW Radiation

Nuclear

Radiation to heat water and then . . . similar to coal. Just a reaction chamber

Local Reactor Columbia Generating Station

- 1,170 MW usually runs as load following. It reacts fast enough.
  - France is ~70% nuclear and they load follow.
- Most nuclear is run as base load, i.e., all the time since low variable cost and high fixed cost.
- Palo Verde (AZ) is larger 3.3GW

So, about nuclear

- So what to do with spent fuel.
- They probably produce less radiation than coal
- Can produce cheap, in the marginal cost sense, power. More on this later.

Natural Gas Conventional and Combined Cycle

- Combined cycle means
  - Taking more than one pass at extracting energy.
  - Spin the turbines first.
  - Take the heat and run a steam turbine.
  - Take the remaining heat and use a different working fluid (with different phase change properties) to extract more.
- CCNG
  - Plants are more expensive
  - Have higher heat rates
- Conventional
  - Cheap
  - Commonly run as peaking units.

Biomass

- Tend to be combined heat and power. Another way of using waste heat.
  - Cogeneration like this is common.
  - We have steam and chill water systems on campus
- While renewable, it is not, in general, clean
  - Particulates
  - Heavy metal concentration
  - etc.
- All this is improving.

Biomas One in Eugene. 30 MW and keeps catching on fire.

Figure 3:

Geothermal

- Drill a hole down to where the temperature is high enough.
  - If it is dry, add water to make steam.
  - If wet, get steam
  - If temp is not high enough, use a few working fluids to generate electricity.
- Run through a turbine.

Neal Hot Spring in Malheur. 30 MW

Figure 4:

Diesel and other Fuel Oils

- You know the drill ...
- Less than 1% in the US for electricity generation.
  - Still common heating fuel.
  - Backup fuel for NG generation
  - May be used in small distributed generation
- More common in less developed countries

Solar Thermal

- You have see the low and mid temperature designs for heating and cooling.
- High temperature designs are:
  - Dish
  - Tower
  - Trough
- Fluids:
  - Oil
  - Salt
  - Water steam
- Low and mid temperature are similar to roof top residential that you have seen.

Hydro

So, you spin a turbine

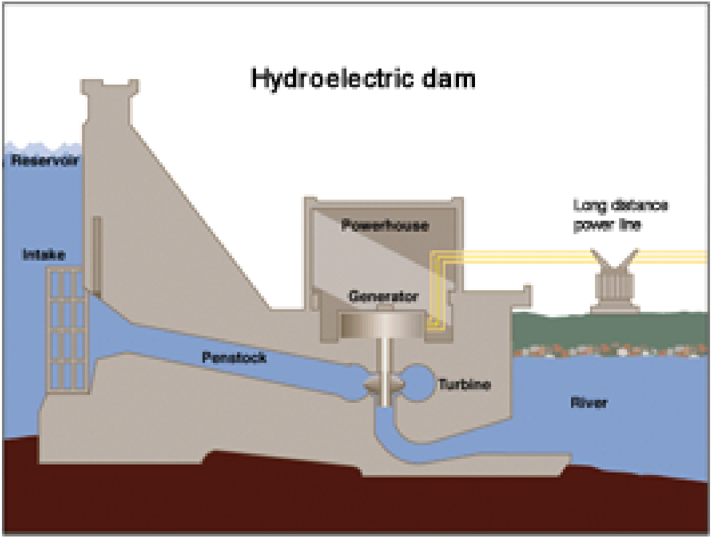
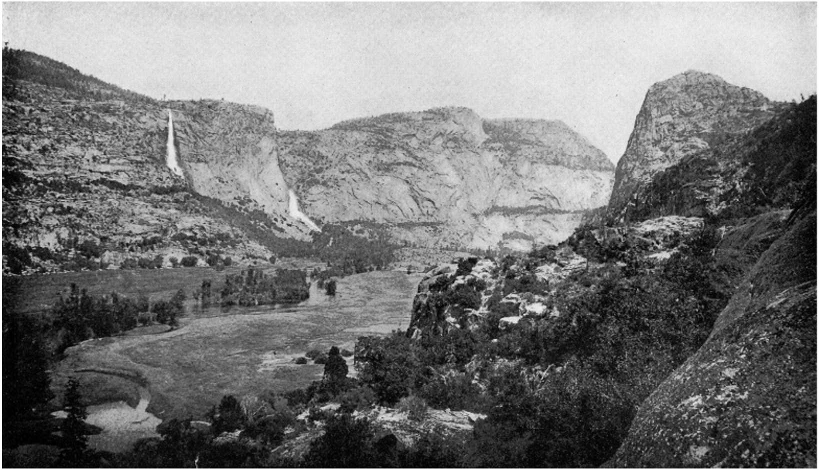


Figure 5:

Hydro can be complex

- Many constraints
  - Intra and interseason storage requirements
  - Temperature and turbidity constraints
  - Treaties and contracts
  - Minimum and maximum flow constraints
  - Dredging
  - Water quality
- Can you go all hydro?
  - US ∼6%
  - Norway ∼95%

Everything Comes with a cost



Hetch Hetchy Valley 1908. Photo by Isaiah West Taber

Figure 6:

Wind

- You find a good wind resource NREL Class 3 and up (http://www.nrel.gov/gis/wind_detail.html)
- Put up a suitably rated 1.5MW windmill. 8MW is the largest I've hear about for land based but read about a ~10MW off shore.
- Maintain them, upgrade them and if need be demo them.
- What people complain about
  - Noise – Can't hear after a mile or two
  - Raptor and bat kills – Less now with larger slower moving designs.
  - Ugly – In in the eye of the beholder.

PV

- Does not spin a turbine.
- PV effect generates DC electricity which is then converted to AC though an inverter

Levelized Cost of Electricity (LCOE) and Levelized Cost of Avoided Electricity (LACE)

- https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf Table 1
  - CC is Carbon Capture.
  - CCS is Carbon Capture and Storage

Economics and History

- Remember that material on transaction cost economics?
  - Induces firms to generate, transport (Transmission) and distribute electricity.
  - Very strong pressure to vertically integrate.
- Large economies of scale produce natural monopolies
  - Declining marginal and average cost of production.
  - Potential duplicative capital expenditures reinforce this.
    - Imagine three power companies with separate poles and connections to your house.
    - Imagine all three of them with transmission lines from UT where they generate power.
  - We tend to regulate these in some way, limiting profit.
- Warnings:
  - Very simple view.
  - With more than one price there are an infinite number of solutions to this problem.
  - Each parameter has a lot of uncertainty.
  - ROR is used in more than just energy.

What Problems are there with Natural Monopolies

- As with all firms with monopoly power:
  - Output is reduced from socially optimal, to increase prices.
  - Dead weight loss from less than socially optimal production.
  - Transfer of surplus from buyers to sellers (Which often shows as super normal profit).
- What makes them special is:
  - Socially optimal output, MC = D, implies negative economic profit.

The Goals of Regulation

- Profits should be normal, same as else where in the market with the same risk.
- Output should at socially optimal, MC = D, not private profit maximizing, MC = MR.
- There should be incentives to produce at lowest cost within each time period.
- There should be incentives to reduce costs from one time period to the next, through R&D, capital investments and technology improvements.

The goals of deregulation

- The goal was not to not regulate. The goal was to only regulate what you must.
  - Control of transmission was stifling cost reductions through competition.
- Don't take the vertically integrated structure, which was dictated by transaction costs as a given.
  - FERC 888/889/2000 split the generation, transmission and distribution parts.
  - ISO/RTO, mostly non-profits set up markets and perform tasks relating to transmission.
  - If you are not in an ISO/RTO you still have to split out generation from transmission. State law does this.

What does an ISO/RTO do.

- Air traffic controllers for transmission. The direct it, plan for expansion, set open prices, pay the people that own it, set prices to avoid congestion.
- Make sure people can see the prices for transmission, Open Access Same-Time Information System (OASIS).
- Organize wholesale markets. Usually day ahead and real time, hour ahead.
- Markets for grid stability services: Regulation up/down, spinning, non-spinning, black start
- Meet NERC, and regional reliability requirements
- Make sure that no one is manipulating the markets and fix the rules so they can't

Rate of Return Regulation

ROR requires normal economic profits but is often visualized in many different ways.

- Setting P=AC
  - In a one price context this sets AR=AC and gives zero economic profit.
  - Increases output from MR=MC to AR=AC but not all the way to efficient MC=D.

ROR Math for fixed price

$$\max_{k,l} pf(k,l) - wl - rk \tag{1}$$

$$s.t. \frac{pf(k,l) - wl}{k} \leq b \tag{2}$$

- Variables:
  - k and l are capital and labor
  - f is production function
  - p is output price
  - w and r are wage and rental rate
  - b is the required rate of return

Sub in $p(f(k,l))$ for monopoly.

You probably want diagrams for this.

What a Natural Monopoly Looks Like in Q-Cost Space

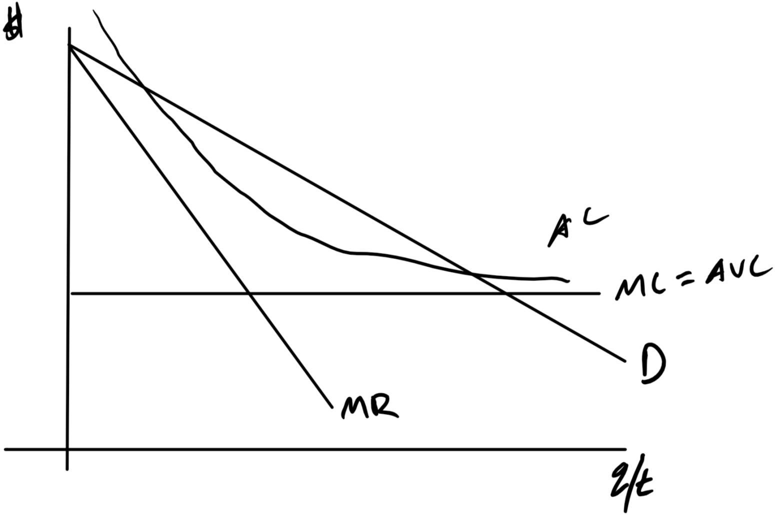
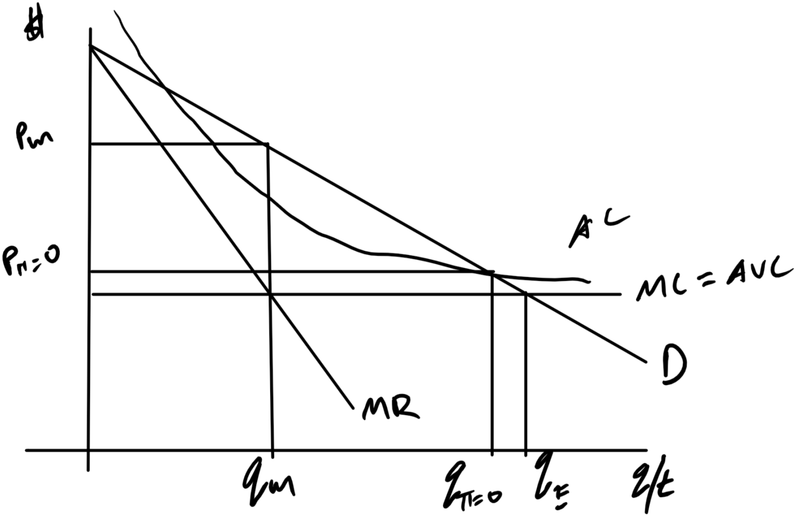


Figure 7:

What Rate of Return Regulation Looks like in Q-Cost Space



Sounds simple but

- How do you know those costs? They may not be known ahead of time. They could be random.
- There is more than one price for electricity and different prices for different customers.
- Rate setting is a periodic judicial process most often using retrospective cost data but also using forecasts.

"Revenue Requirement"

$$RR = v(q) + bRB$$

- Note variable change from above.
- The revenue requirement (RR) must be satisfied by the pricing system.
  - Why the simple versions with a single price is P = AC.
  - No guidance on what to do when there is more than one price, except find a way to allocate costs to those prices.
- Most commonly the RR:
  - Passes variable costs, v(q), like fuel and wages though to be included in prices.
  - Has a target return on capital, b, which is known to attract capital and compensate investors for risks.
  - That rate of return is applied to the Rate Base, RB, which is analogous to capital.

“Cost” is much more complex than that

- We don’t put a price on every service to the end user.
- We often pay for one service, like transmission, by lumping it in with a different service, say energy kWh.
- We also will use average values of cost and give one price to everyone, like residential kWh.
  - The cost at peak is higher than middle of the night.
  - The cost in rural areas is higher than urban
- Other objectives that make it so cost and price don’t align.
  - Less expensive to poor
  - Incentivize conservation
  - Cognitive limitations

Pictures with lots of cost drivers

- One House (Certainty Costs):
  - Connection: Just having access is a service
  - Demand Charge kW: How much you use at most determines the fixed cost of local distribution
  - Coincident Peak kW_c: How much you consume at system peak. Your contribution to the fixed and sunk cost of transmission and generation.
  - Energy Use kW: Many choices here, do you average all the costs, integrate individually?
- System (Randomness Costs):
  - The random squiggles (high frequency noise): Regulation
    - Do you charge for individual variation or based on the incremental effect
  - Larger movements (Lower and Lower still frequency noise): Spinning and non-spinning reserve.
  - Black Start (How to start after blackout)
  - Maintenance and monitoring: SCADA, tree trimming, down lines, etc.

What do ROR incentives do?

- If I can pass all variable costs on to the customer . . .
  - Regulatory Accounting Standards just like GAAP and GASB.
  - Regulators scrutinize and decide if an expenditure is allowable expenditure, in the rate base, or shareholder responsibility.
- Flip side, if I make investments or go through the effort to reduce costs, the savings don't result in more profit
  - You only see the cost and risk.
  - The customer sees only the benefits.
- Not bad if there are long periods between rate changes.
  - If you reduce costs you see the benefits between rate changes.
  - If your costs are high, you eat the costs between rate changes.

Terrible cost savings incentives.

How else can I increase profits?

- Add more things to the rate base.
- This is the A-J effect.
  - Firms prefer to deliver services by investing in capital.
  - The rate of return, b, does not increase but if you increase RB your revenue increases and your profit, i.e., net income increases.
  - Why Demand Side Management had an initial battle:
    - Rate payer advocates wanted it to pass through as expense.
    - Shareholders wanted it counted just like a power plant, in the rate base.

What ROR Regulation looks like in Input-Output Space.

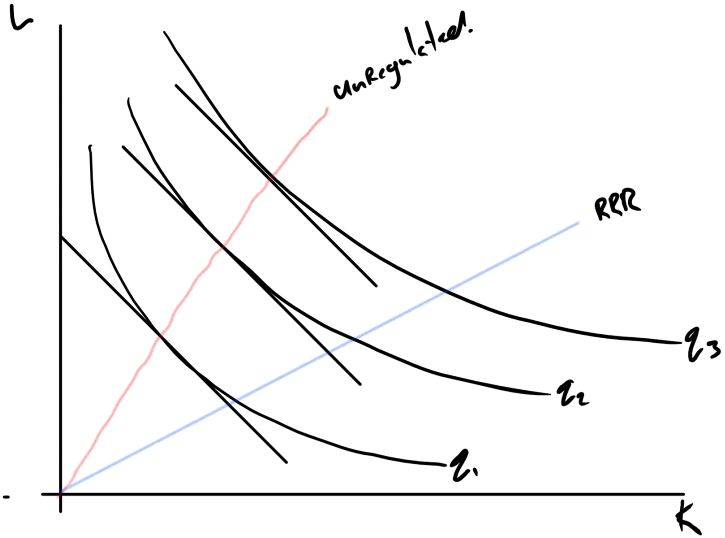


Figure 9:

What about b?

- b is actually more than one number.
- Bond rate necessary to attract lending.
- Return on common equity to attract shareholders
- There could be others.

Yardstick Regulation

Yardstick competition (Shliefer 1985) `http://stats.lib.pdx.edu/proxy.php?url=http://www.jstor.org/stable/2555560`. Don't use the firm's own costs, use the costs of an identical firm elsewhere.

- Creates cost competition where none previously existed.
  - If you reduce costs and your yardstick matches do not, you get higher profits.
  - If you reduce your cost of capital and your yardstick matches do not, you get higher profits.
- The usual worries
  - Benefits to colluding
  - Odd scale effects and competitor shopping
  - Mergers
    - Merging with your yardstick competitor may be a very good thing.
    - Mergers or reverse may be motivated the yardstick competitors.

CPI-X or Price Cap

CPI-X. Prices increase periodically year by CPI less some amount X. X is chosen as an average rate of cost savings.

- Incentives to reduce costs
  - If you reduce costs faster than X, you get to keep it.
  - No reference to another firm.
- But . . .
  - Where did you get X?
  - How do you know costs will on average go down?