A Generic Power Plant and Grid

John C. Bean

Outline

Most power plants = Heat source + boiling water kettle + propeller + generator

- Including coal, nuclear, biomass/biofuel, and one type of natural gas (CCGT)
  - Hydro and wind plants omit the heat source & kettle
    - But photovoltaic power plants (alone) are completely different

Our demand for their power is very cyclic = Base Power + Dispatchable Power

- Massive steam plants cannot efficiently meet this cycle (only hydropower can)
  - And only one type of natural gas plant (OCGT) can deal well with its 2-3 hour peak

Combining many power plants into a grid requires scrupulous synchronization

- And even that falls apart if one tries to transmit AC power over long distances
  - Where the peaks in current and peaks in voltage cease to track one another

Which, accelerated by green energy, is pushing us toward high voltage DC power transmission

- As enabled by transformers + diodes + capacitors

(Written / Revised: July 2019)

A Generic Power Plant and Grid

Our natural tendency is to focus on only certain types of **power plants**

Those we revile OR

Those we see as technological saviors OR

Those closest to our personal experience and/or expertise

But power plants are just pieces in the huge puzzle of an **Energy System**

And, of course, puzzle pieces are USELESS IF THEY DO NOT FIT into a puzzle

Yes, in the future we hope to assemble very different energy puzzles

For instance, ones built around new solar and or wind puzzle pieces

But those new puzzles will still require a FULL SET of compatible pieces

This note set provides an overview of how energy system pieces fit together

Wikipedia offers this depiction of a generic electrical grid:

Which includes some **very useful numbers** about U.S. power plants:

Their typical "capacity" (max output) is ~ 600 MW (Range: 100 – 2000 MW)

From the **U.S. Energy Production & Consumption** (pptx / pdf / key) note set:

U.S. power consumption is ~ ½ TW:

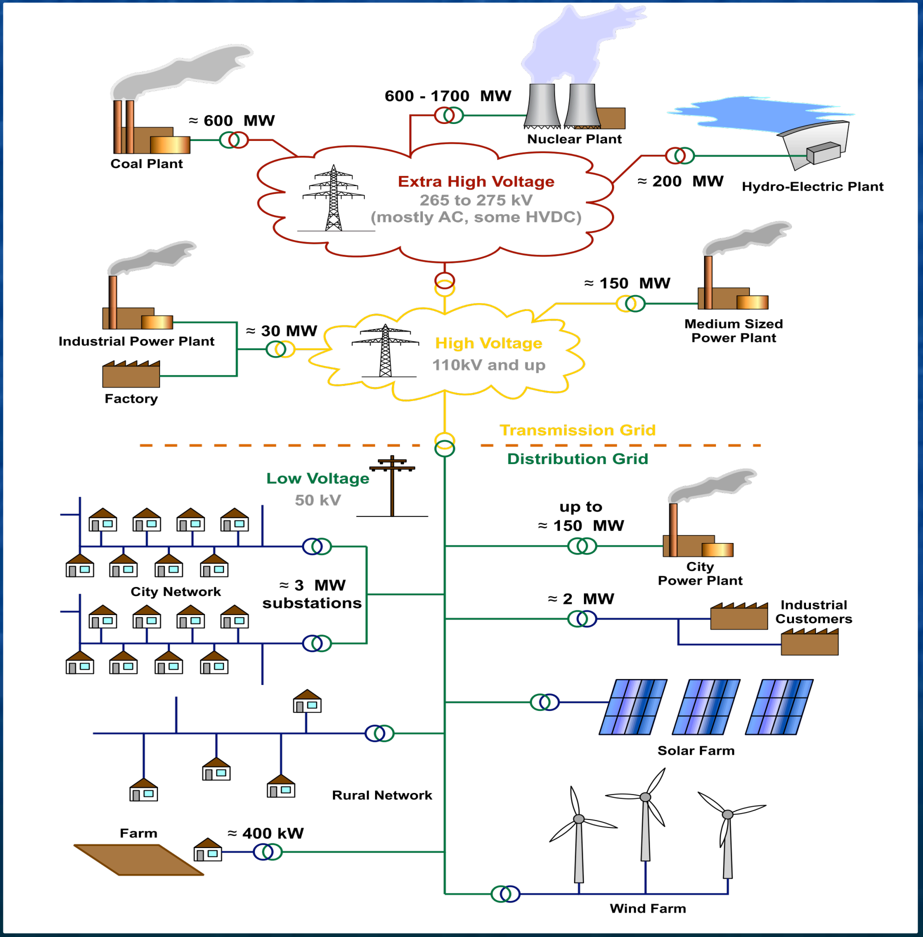
(½ TW) / (600 MW) ~ 800 plants

According to the EIA the actual number,

which includes small/old plants

and small/new technology plants

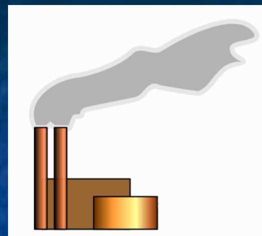
is a bit over 8000 [1]



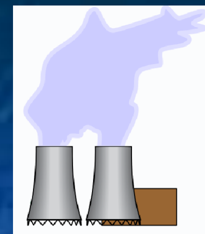
1) https://www.eia.gov/tools/faqs/faq.php?id=65&t=2

Figure: http://en.wikipedia.org/wiki/Electrical_grid

From that illustration, we can extract these power plant icons:



OR



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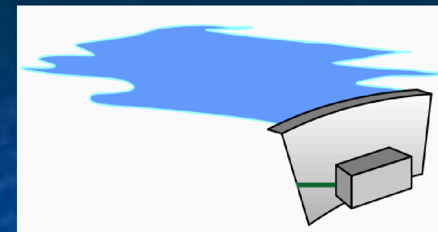
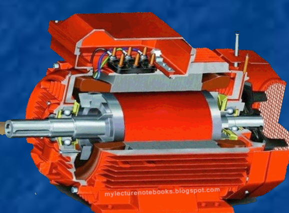


These power plants appear to be very, very different

But while their outward appearances do indeed differ

The MAJORITY of power plants consist of this:



http://www.chuckbauman.com/real-flames-photos.htm

http://knowledge.wharton.upenn.edu/article/stressed-work-youre-alone/

http://www.nauticexpo.com/prod/baeksan-propeller-co-ltd/boat-propeller-shafts-26399-173731.html

http://mylecturenotebooks.blogspot.com/2013/07/how-does-generator-create-electricity.html

That is:

1) **A heat source**

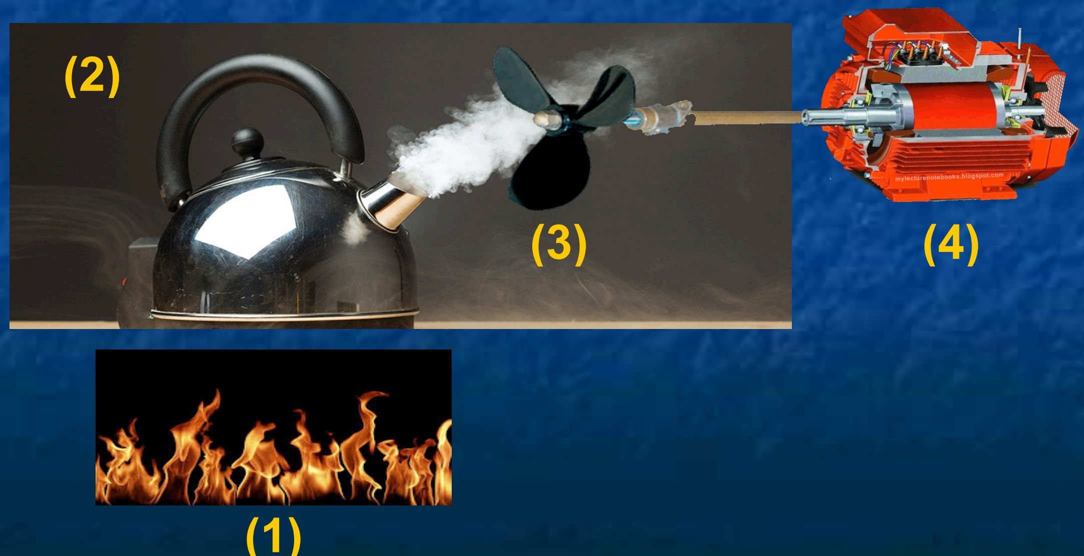
2) **A boiler** in which water is heated to above 100°C

    Causing it to form steam, which expands 1700 times in volume

3) **A propeller** that is turned by the resulting high pressure steam flow

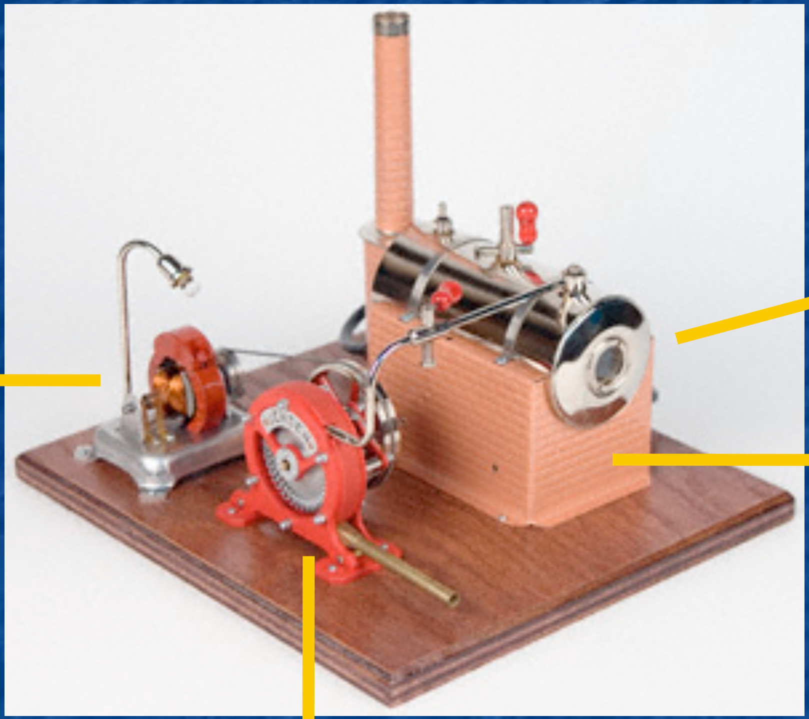
    Although it is then called a steam turbine (or just "turbine")

4) **An electrical generator** (from the preceding note set) turned by that propeller



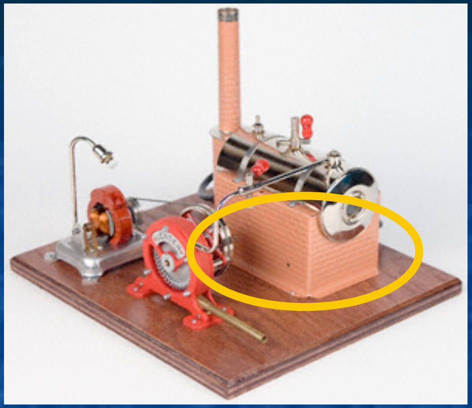
This is so simple that:

You can actually buy your own table-top steam-powered power plant: [1]



1) https://www.ministeam.com/acatalog/Turbine-Power-Plant-JN95G.html

How U.S. steam-powered plants produce their steam (in 2018): [1]



27.4% of them boil water by burning **coal**

19.3% of them boil water inside **nuclear reactors**

1.5% of them boil water by burning **biomass**

~1% of them boil water by burning **other things**

0.4% of them boil water by tapping into **geothermal heat**

And, while **35.1%** U.S. power plants burn **natural gas**,

only one type of natural gas power plant (CCGT) boils water

See note set on Fossil Fuels (pptx / pdf / key) for details

1) See my note set on U.S. Energy Production & Consumption (pptx / pdf / key)

*How **efficient** are such steam-powered powered plants?*

That is, what is the ratio of: **Electrical Energy Output / Heat Energy Input ?**

Unlike steam locomotives, steam power plants conserve water by operating in a **cycle**:

- Heat is applied to the steam, causing it to increase in temperature & volume
- The steam's volume expansion then turns a turbine connected to a generator
- Cooling is applied to the steam, causing it to decrease in temperature & volume

In 1824**, Nicolas Carnot** produced a weirdly idealized model of this cycle:

It assumes, once vaporized, that water is never allowed to recondense AND that:

A heat source causes it to expand (while remaining at ~ constant temperature!)

The heat source is then removed, temperature changes, expansion continues

A cooling source causes it to contract (again, while at ~ constant temperature!)

The cooling source is then removed, temperature changes, contraction continues

Carnot's weirdly idealized cycle, shown pictorially:

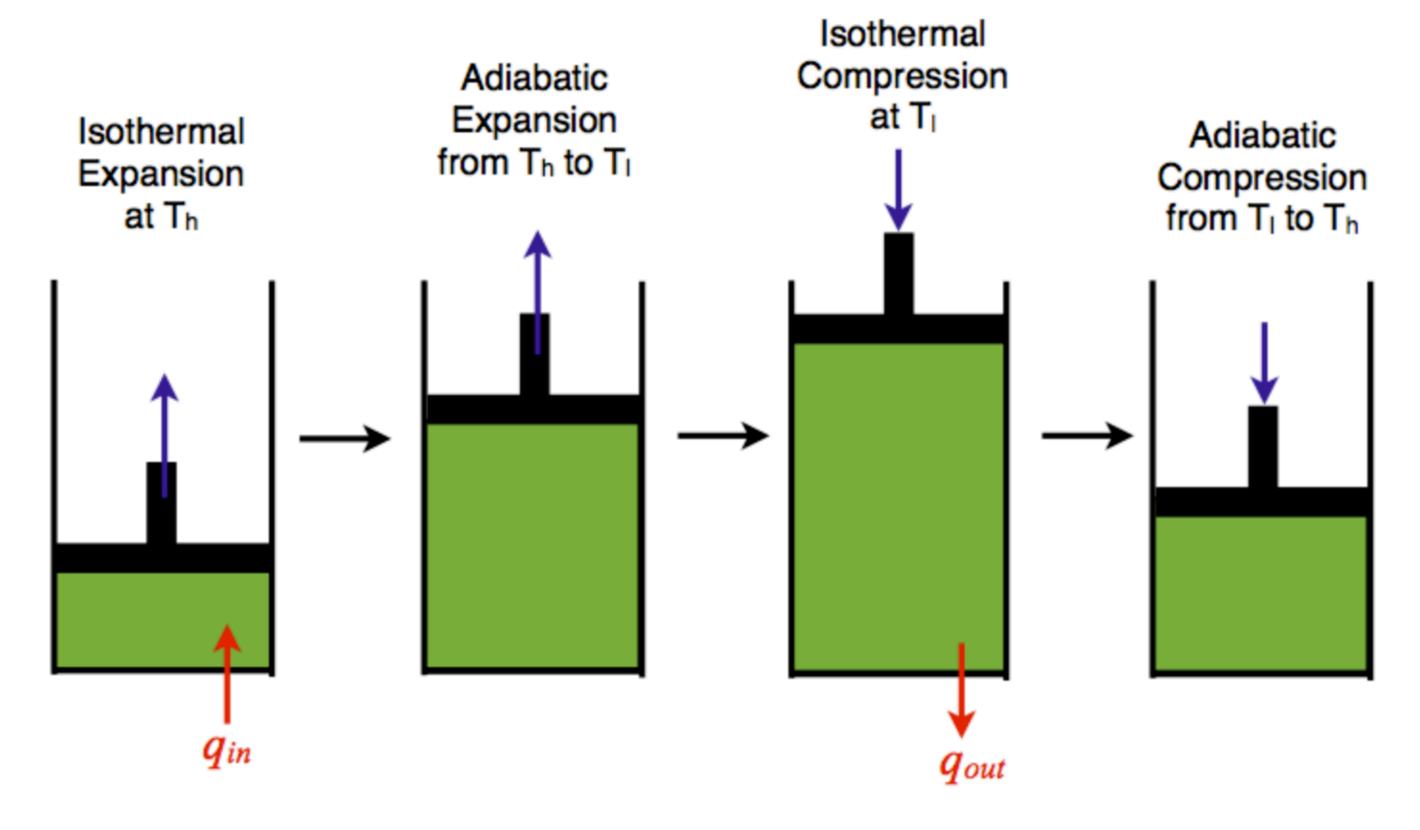


***Figure 1**: An ideal gas-piston model of the Carnot cycle.*

"Isothermal" = While at constant temperature

"Adiabatic" = While zero energy is allowed to flow in or out

https://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Thermodynamics/Thermodynamic_Cycles/Carnot_Cycle

Only via this weird idealization could Carnot calculate an efficiency:

Carnot Cycle "heat engine" efficiency = $(T_{high} – T_{low}) / T_{high}$

Where T_{high} = Temperature of the heating source ("heating reservoir")

And T_{low} = Temperature of the cooling source ("cooling reservoir")

But in **real steam power plants**, steam IS repeatedly condensed back into liquid

With makes them examples of the much more complex "**Rankine Cycle"**

Further, in both the **Carnot Cycle** and **Rankine Cycles**:

Heat application => Simultaneous steam expansion + temperature increase

Cooling application => Simultaneous steam contraction + temperature decrease

The Carnot Cycle thus provides only an idealized upper limit on efficiency

But it is nevertheless used to highlight a power plant design imperative:

Maximize the steam's low to high temperature excursion!

*How efficient are **real-life** steam power plants?*

Traditional oil & coal-fired plants are relatively simple and unconstrained

Which facilitates their use of very high steam temperatures (e.g., 540°C [1])

Their resulting real-life efficiencies are 32-42% [2] ("typical" ~ 33-35% [1])

New "ultra-supercritical" coal plants (such as the Karlsruhe RDK 8) reach 620°C

Which has allowed it to achieve a real-life efficiency of 46% [3]

Nuclear power plant cores are complex and multi-functional,

constraining their core temperature/pressure, lowering efficiencies to 30-35% [1, 2]

Solar thermal power plants are new, with different still rapidly evolving designs

California's Ivanpah water-vapor (steam) plant was designed for 29% efficiency [4]

Newer oil-vapor / molten salt plants should be substantially more efficient

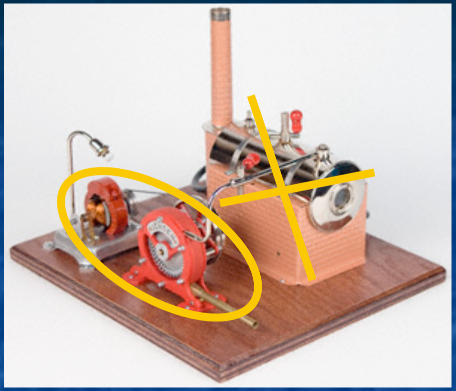
1) Chapter 5 in Engineering and the Environment by Edward S. Rubin

2) Steam Turbine Power Plants - Engaged in Thermodynamics: http://cset.mnsu.edu/engagethermo/systems_stpp.html

3) RDK 8s Three Little Words: http://www.powerengineeringint.com/articles/print/volume-18/issue-5/Special_Project_Report/rdk-8s-three-little-words-efficient-reliable-and-flexible.html

4) https://en.wikipedia.org/wiki/Ivanpah_Solar_Power_Facility

*Leaving what types of **non-steam** U.S. power plants?*



7% of U.S. power plants instead turn the turbine & generator via **hydro power**

Converting water's gravitational potential energy at nearly 90% (!) efficiency [1]

6.6% of U.S. power plants instead turn the turbine & generator via **wind power**

Converting wind's kinetic energy at about 40% efficiency [1]

Plus: The 1.6% of U.S. electrical power that comes directly from photovoltaic cells

And technologies so minor that the E.I.A. does not even provide data about them

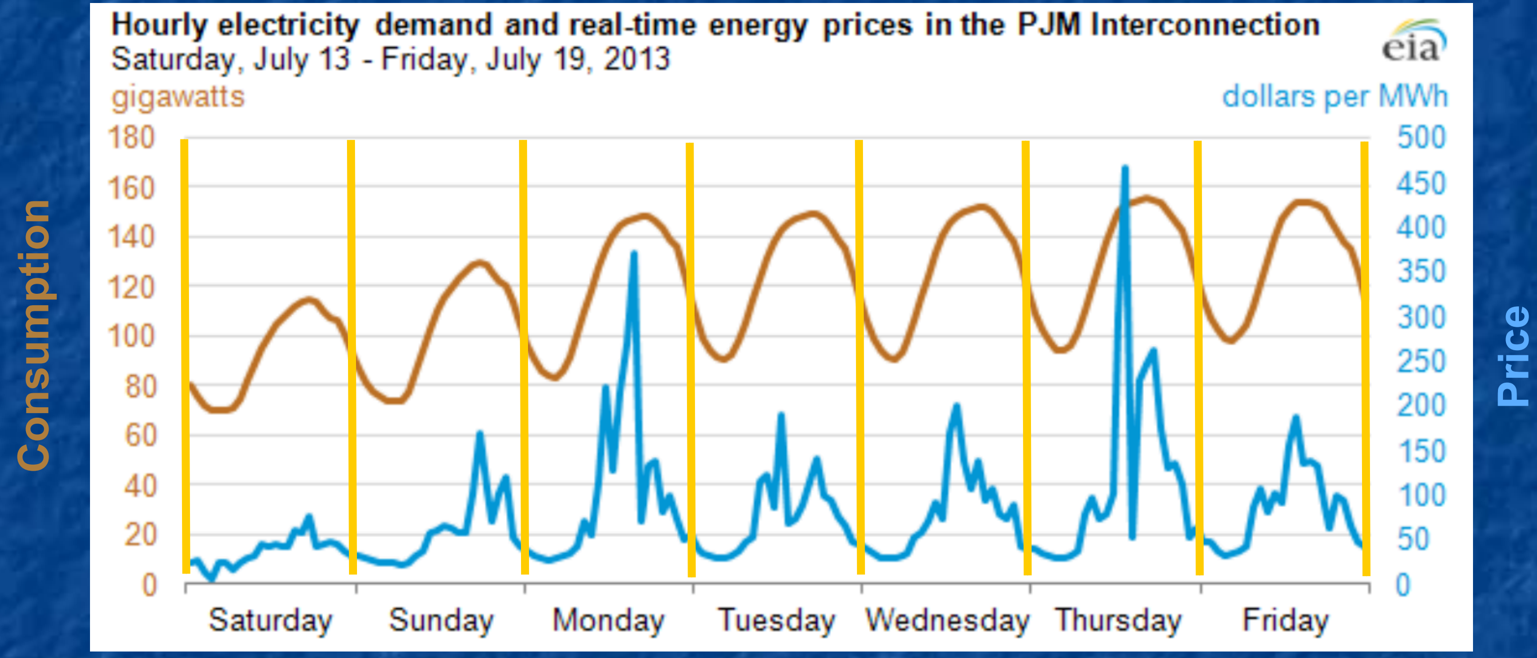
See **U.S. Energy Production & Consumption** (pptx / pdf / key) notes for info on U.S. power

1) Chapter 5 in Engineering and the Environment by Edward S. Rubin

But our demand for electrical power varies:

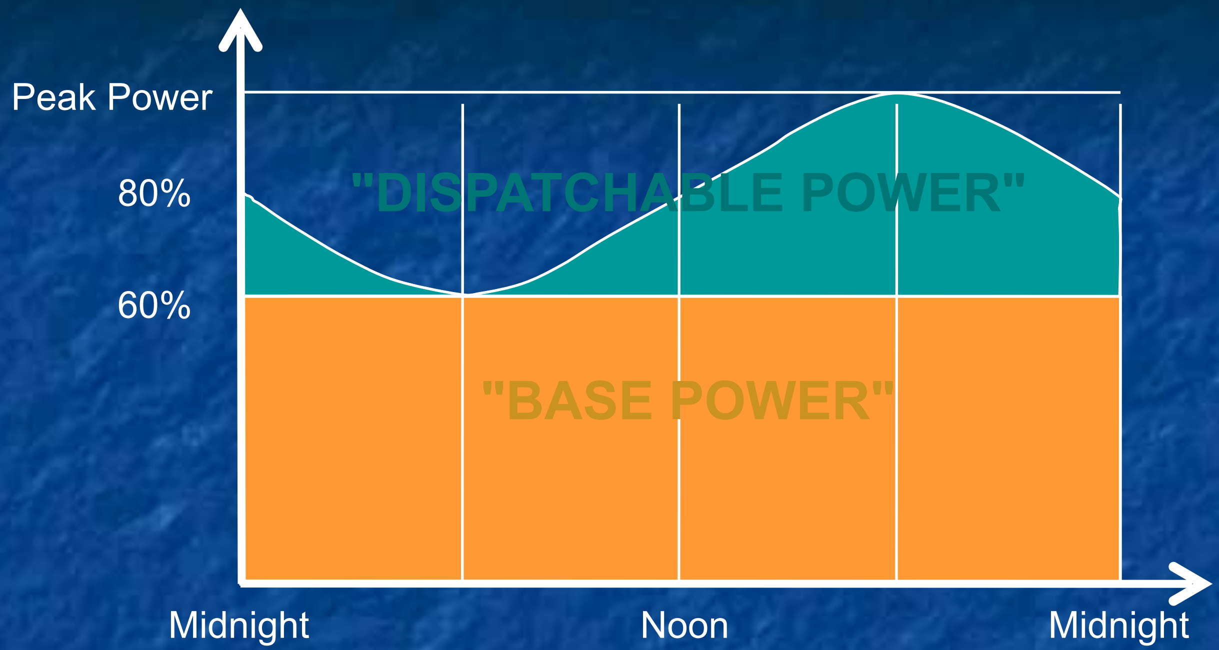
Our typical daily cycle of power consumption (**brown**) and its price (**blue**):

(also from that **U.S. Energy Production & Consumption** (pptx / pdf / key) note set)



Source: https://www.eia.gov/todayinenergy/detail.php?id=12711 (to which I've added the yellow lines)

A typical daily demand cycle thus resembles this:



There is a **"BASE"** power demand (from 0% up to about 60% of the demand peak)

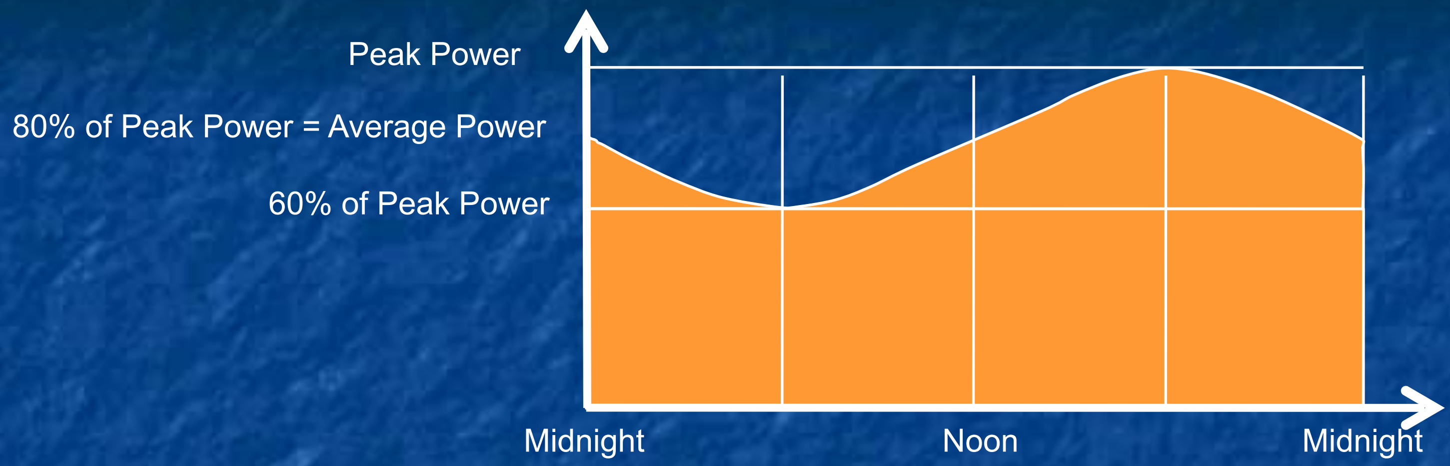
On top of this is an oscillating **"DISPATCHABLE"** power demand

Which cycles up from about 60% of peak, to 100% of peak at about 6 pm

Which gives that ~ sinusoidal oscillation an average of ~ 80% of peak power

Which also makes the **average daily power ~ 80% of peak power**

Power plant production should follow this same cycle:



BUT THERE IS A BIG PROBLEM:

Only one type of power plant can efficiently follow such a cycle

HYDROELECTRIC PLANTS

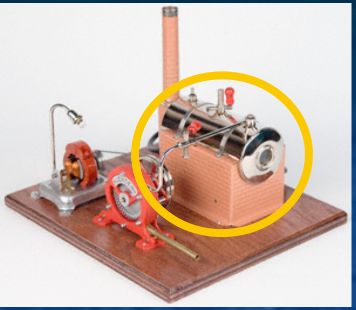
Which need only throttle their water input valves more open or closed

But hydroelectric plants can now supply less than 7% of U.S. power demand

What's the problem our majority steam-driven power plants?!

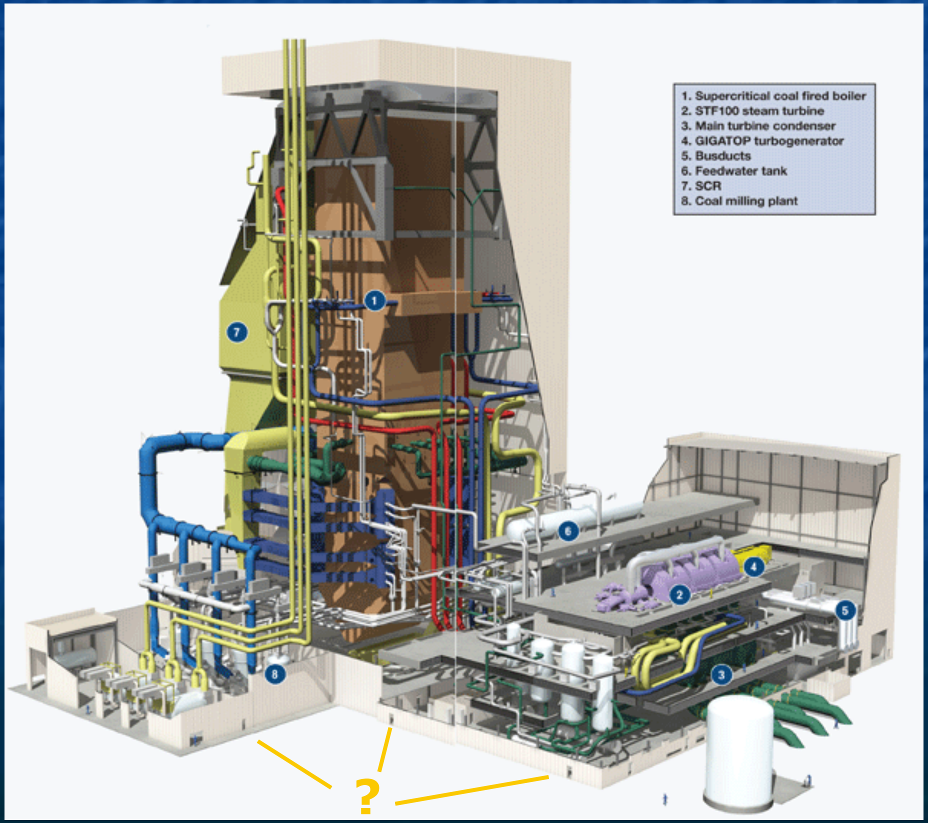
The problem is with their boilers

Which, rather than resembling this toy's boiler:



Instead look more like this:

See those minuscule rectangles at the bottom? They're doors for the employees



http://www.powerengineeringint.com/articles/print/volume-18/issue-5/Special_Project_Report/rdk-8s-three-little-words-efficient-reliable-and-flexible.html

An aerial view of that boiler once it was enclosed:

The new 912 MW #8 boiler at the RDK coal power plant in Karlsruhe Germany: [1]

Photo: https://www.ksb.com/ksb-en/Products_and_Services/Energy/selected-power-plant-ksb-en/rdk-karlsruhe-germany/330208/

Boilers must heat water from ambient temperature to over 100°C

But you get ZERO power out until you cross 100°C and steam begins to form

All the heat energy expended in GETTING TO 100°C is, in a sense, wasted

As is energy heating the very thick steel of the high-pressure boiler and piping

As is heat flowing into the supporting and enclosing structures

1) http://www.powerengineeringint.com/articles/print/volume-18/issue-5/Special_Project_Report/rdk-8s-three-little-words-efficient-reliable-and-flexible.html

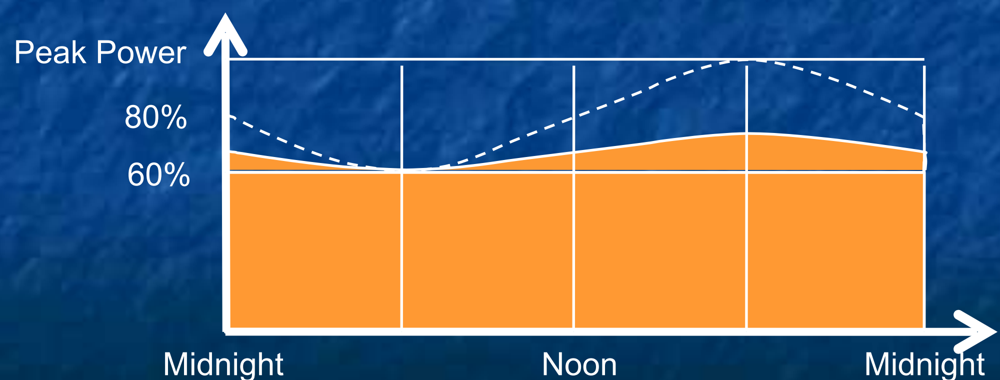
*And it takes **4-8 hours** for steam boilers to reach **full** temperature !* *(1)*

And once there, it takes MORE time to significantly increase/decrease steam output

During which heat energy will again be used wastefully

Coal, Nuclear, Biomass/fuel steam plants thus best produce our **Base Power**

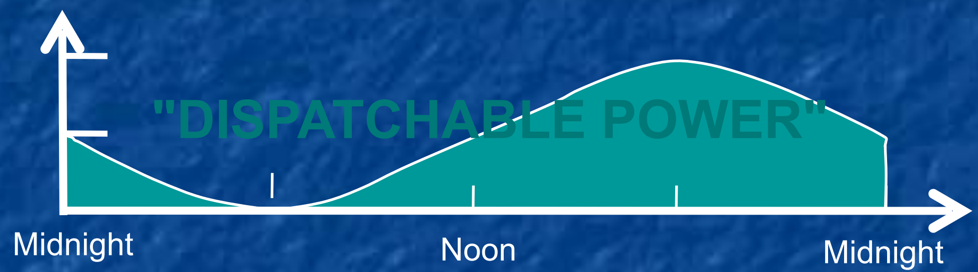
Or, with some throttling (and thus lower operating efficiency), perhaps this:



1)To Survive, Power Plants Must Become More Flexible: https://www.reuters.com/article/coal-power-generation/column-to-survive-coal-power-plants-must-become-more-flexible-kemp-idUSL5N0J42YG20131119

Leaving us with the problem of producing DISPATCHABLE POWER

Which is that big rise in our power consumption in the late afternoon / evening:



Throttling of hydroelectric or steam plants can help out a little bit

But they still cannot deal with the 2-3 hours of PEAK evening consumption

We instead add **Peaking Power Plants** which turn on ONLY for those 2-3 hours

Powering up and down very quickly, these plants **cannot use steam**

Sitting idle for 21-22 hours a day, they **must be inexpensive to build**

Even if that means using technologies that are **expensive to operate**

Today's choice for Peaking Power Plants: Natural Gas OCGT

Where OCGT stands for **Open Cycle Gas Turbine**:

= **A natural-gas-fired jet engine attached directly to a generator**

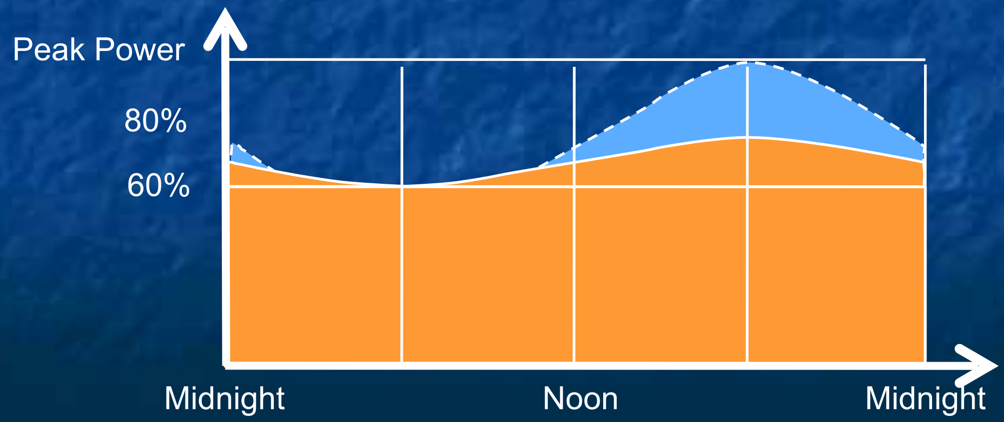
- Which can go from full off to full on in seconds

- Is far simpler and thus far cheaper to build/buy than other power plants

- But which, while on, consumes expensive natural gas fuel

Fully described, along with CCGT, in **Fossil Fuels** (pptx / pdf / key) note set

Giving us today's typical power production profile:



Peaking Power:

OCGT + Hydro

Throttled Base Power:

Coal, Nuclear, Hydro, CCGT
Biomass/fuel

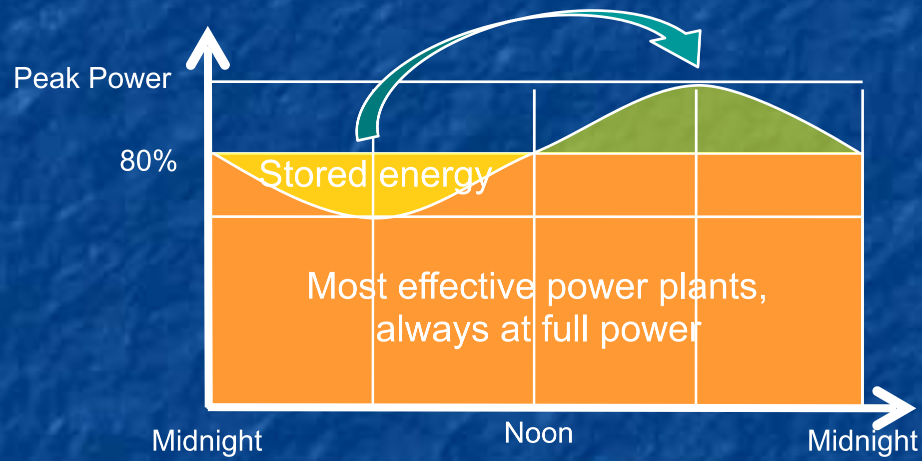
But there IS another possibility:

Choose the cheapest cleanest type(s) of power plants

Run them all day at full power, maximizing their bang per capital buck

Size them so their power = 80% of peak power = Average daily power

Then store excess power produced early in the day for use later in the day



But we cannot now store that much energy

And even MORE storage will be required for a wind or solar driven grid

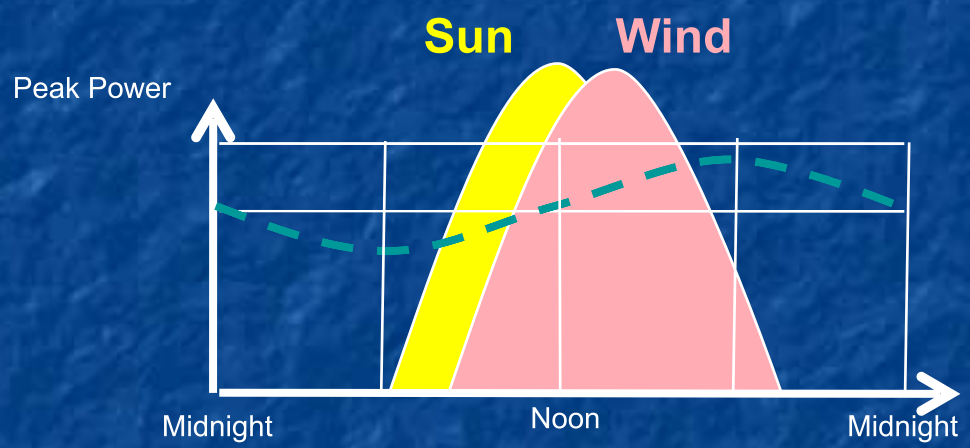
(Hence my half note set on grid batteries, and full note set on emerging energy storage technologies)

What happened to our 6.6% wind power, and 1.6% solar power?!

Aside from now being sort of bit players:

Wind only **weakly** supports our demand cycle (peaking in late afternoon)

And solar is absolutely **worthless** in the evenings!



In fact, if/when wind + solar grow to more than ~ 15% of our power,

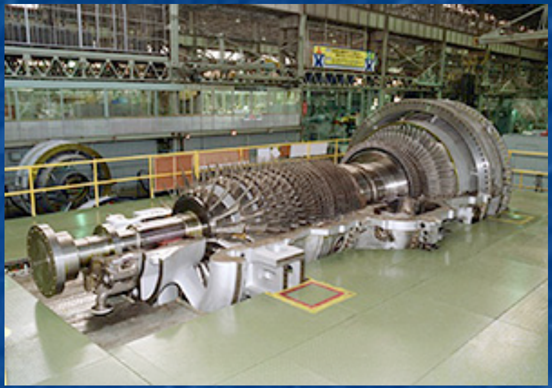
midday power storage will no longer be an interesting option

MASSIVE MIDDAY POWER STORAGE WILL BE AN IMPERATIVE!

But moving to finish our overview of power PLANTS:

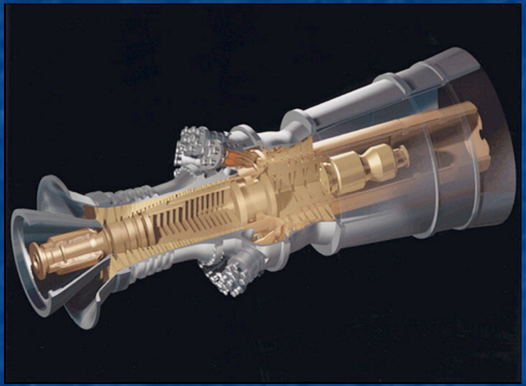
Turbines, which are in **ALL** power plants (except photovoltaic plants), look like this:

Steam plant:



http://fossilfuel.energy-business-review.com/news/mitsubishi-to-supply-turbines-for-400mw-zerger-gas-fired-power-plant-in-turkmenistan-010416-4853879

Natural Gas Plant:



http://en.wikipedia.org/wiki/Fossil-fuel_power_station

Hydroelectric Plant:

http://en.wikipedia.org/wiki/Francis_turbine

It's no coincidence that the left & center turbines closely resemble jet engines:

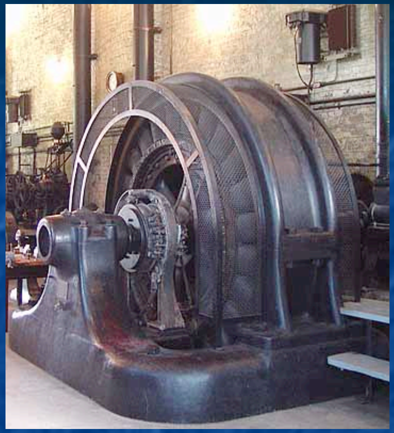
They are ALL driven by expanding gases (be it steam or combustion gases)

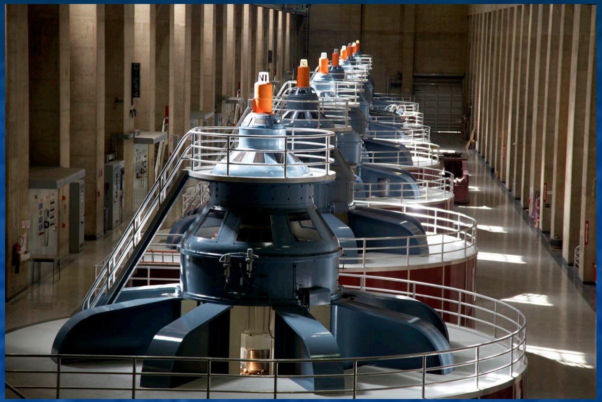
Some companies (like GE) actually make **both** power plant & jet turbines

But the 1000 times greater density of water demands much sturdier designs,

such as that in the "Three Gorges" hydropower turbine shown at the right

Those turbines turn electrical generators that look like this:





But despite their vastly increased size

these still clearly resemble the AC motor from my woodworking tool!

Because, at their heart, they **DO** still have the same components:

A stator (likely an electromagnet rather than a permanent magnet)

And a rotor (almost certainly an electromagnet)

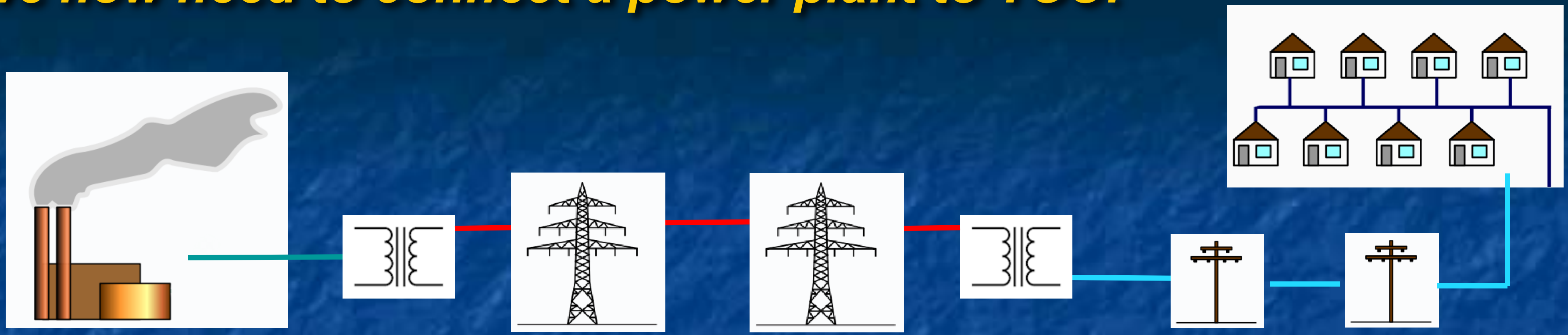
All just waiting for something to **turn** that rotor!

http://www.inn-california.com/valleys/sacramentoC/powerplant.html

http://coalfiredpowerplants.blogspot.com/p/steam-electric-generators-look-at.html

http://upload.wikimedia.org/wikipedia/commons/thumb/a/a7/Water_turbine_grandcoulee.jpg/683px-Water_turbine_grandcoulee.jpg

We now need to connect a power plant to YOU:



"Whoa! Things suddenly got awfully complicated!"

Yes, if you don't want to waste power while transmitting it **to** your house!

Electrons flowing through wires ("electricity") bump into metal atoms

transferring some of their energy to those atoms (**as heat**)

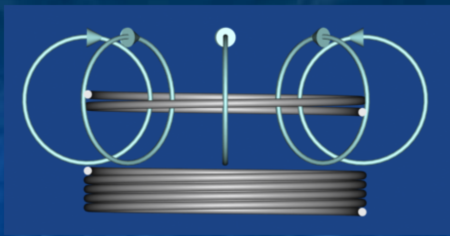
This is called Resistive Power Loss

To minimize resistive power loss, you must minimize electron flow:

You can exploit the fact that electrical power = Current flow x Voltage

by choosing to transmit power as (low current) x (high voltage)

You reduce electron current via the last note set's ***AC transformers***



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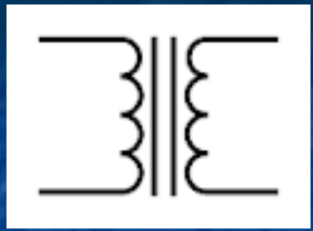
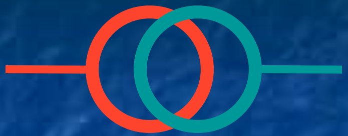


Also sometimes represented as:



Which consist of two coils of wire coupled by a **changing** magnetic field:

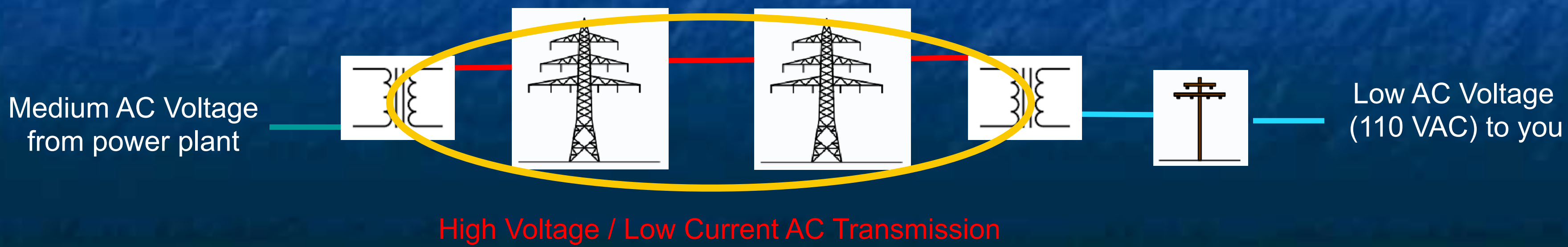
Constantly changing AC of one voltage & current is sent into the 1st coil

Creating a variable magnetic field expanding/contracting through the 2nd coil

Which "Induces" AC of a different voltage & current out of that 2nd coil

But with the power input still equaling the power output via $\mathbf{V_{in} \times I_{in} = V_{out} \times I_{out}}$

Transformed high voltage / low current power is sent through the long distance links:



The transformers are located in "switching yards" or "substations"

http://rtcmagazine.com/articles/view/102190

http://en.wikipedia.org/wiki/Electrical_substation

Or right in your neighborhood:

http://en.wikipedia.org/wiki/Transformer

The full sequence of AC voltages, power plant to your home, may be:

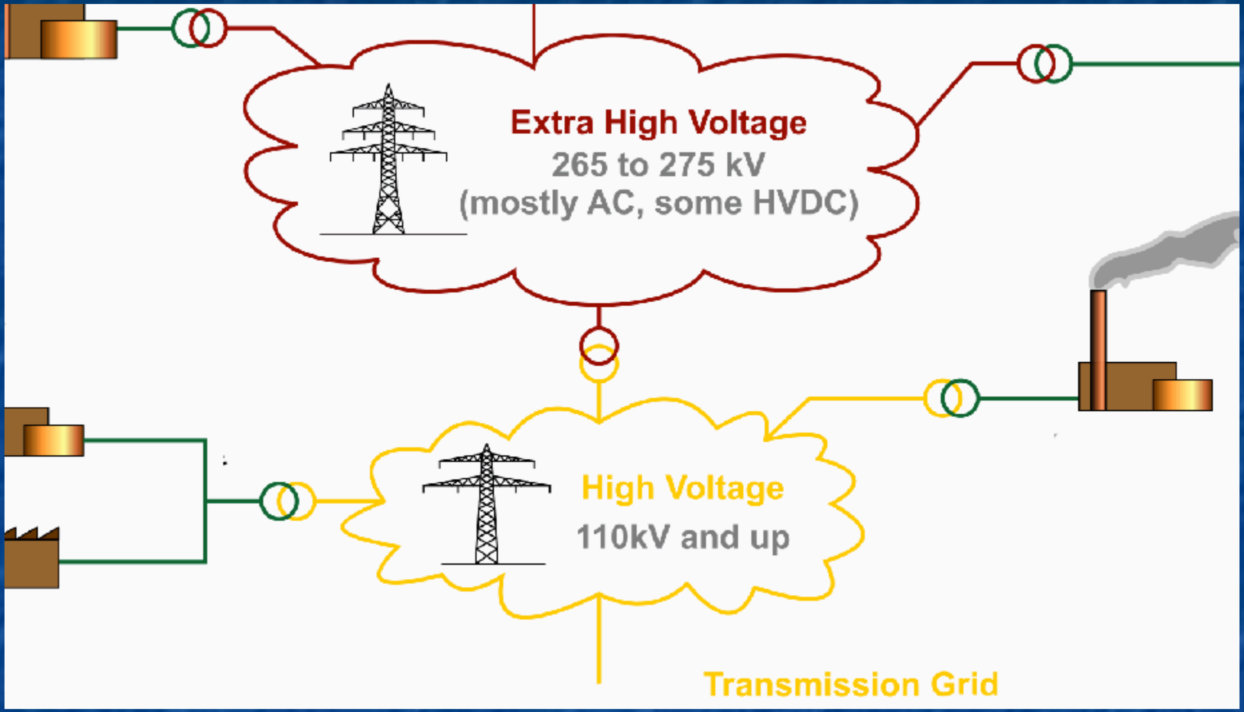
25 kV AC (from power station) => 275 kV AC (long distance transmission)

=> 100 kV AC (regional transmission) => 25 kV AC (local distribution)

=> 110 VAC (your home)

The quest for efficient transmission can drive voltages ***extremely*** *high:*

To hundred's of thousands or even a million volts – just to minimize current flow!

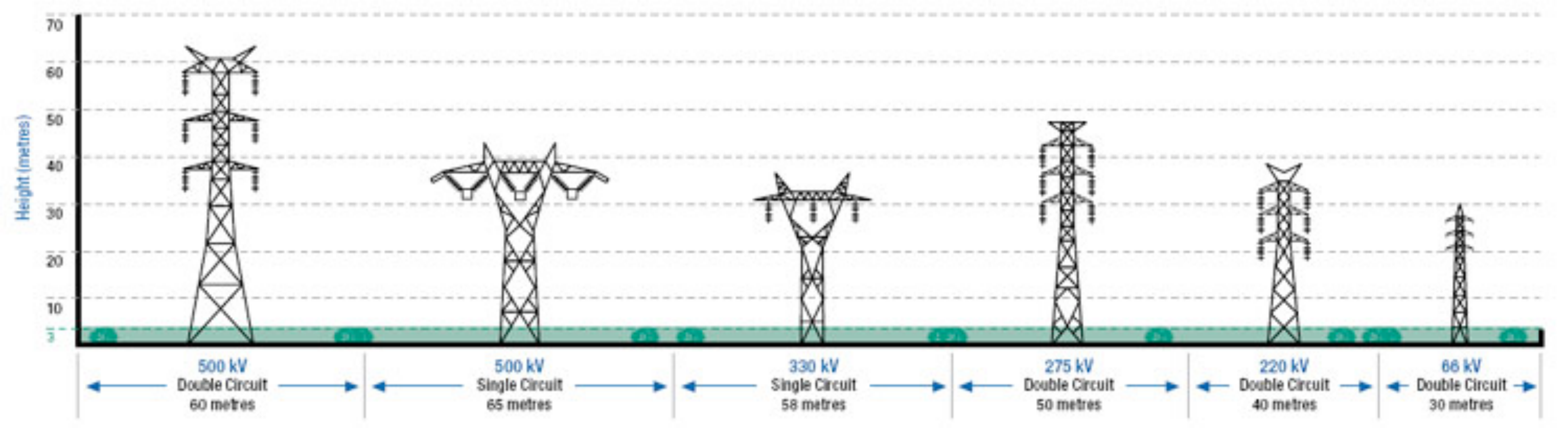


Which is also **why long distance transmission towers have to be so tall:**

Towers use the air itself as an electrical insulator

So wires must be very far from each other, and very far from the ground!

You can even identify transmission voltage from tower size:



http://www.ausnetservices.com.au/Electricity/Safety+&+Preparedness/Transmission+-+Easement+Use.html

Or by counting number of bell shaped insulator disks:

Rule of thumb: One disk per 10 kV of voltage used [1]

http://en.wikipedia.org/wiki/Insulator_%28electricity%29

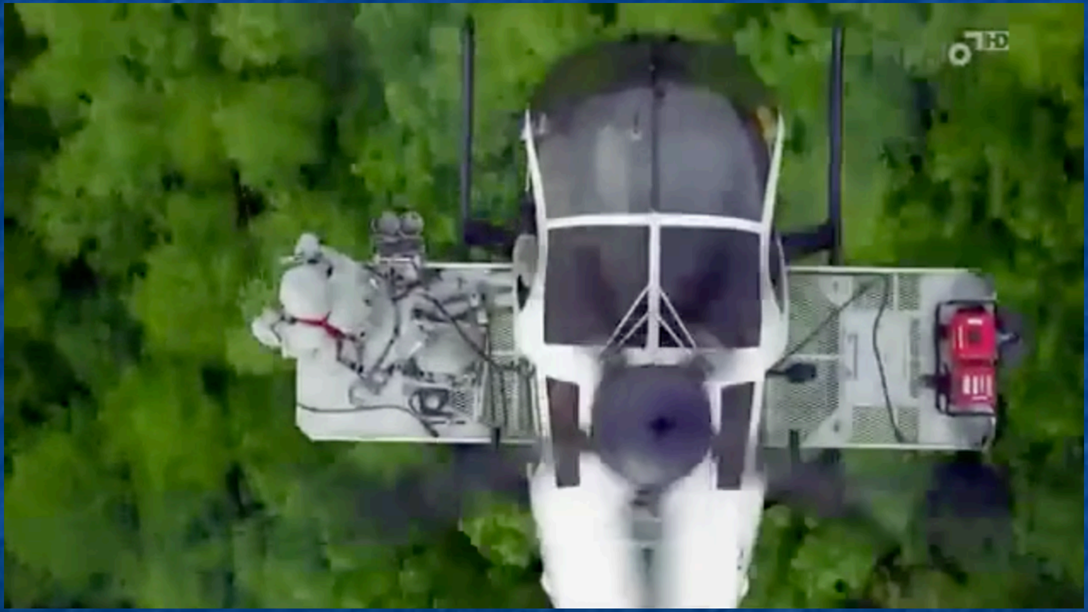
1) Source: Electric Power Systems – A Conceptual Introduction, page 181 – Alexandra von Meier

A Digression:

How do you service high voltage transmission lines & towers?

With the same cranes that were (presumably) used for their assembly?

No, at least not always:

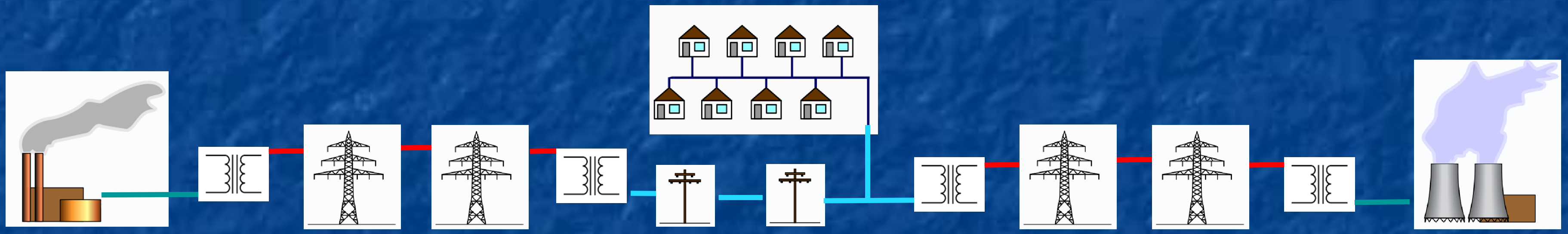


Resources Webpage: Video of Helicopters in Action

A problem: "Grids" almost always combine ***many power plants****:*

For redundancy, and/or to take advantage of plants' natural production cycles . . .

So our "generic" grid grows into something more like this:



Two (or more) power plants simultaneously supplying AC power => A Problem

AC voltage goes up & down, pushing electrons, then pulling electrons

If 1st plant pushes electrons while 2nd is trying to pull:

2nd plant will start absorbing 1st plant's power => Boom, sparks, fires . . .

They must push together & pull together = AC voltages must synchronize

*To synchronize AC from two **nearby** power plants:*

1st plant starts up (or is already running)

2nd plant, monitoring power from 1st plant, starts turning its generator shaft

- It speeds up, matching phase and speed to 1st power plant
- **Only when matched** does it connect itself to the grid

How accurately must 2nd plant synchronize before it connects? [1]

- Its AC voltage amplitude has to be within 5% of 115 Volts
- Its frequency has to be within ~ 0.067 Hz of 60Hz
- Its phase must be within 10° (i.e., 1/36th of cycle)

From top to bottom: synchroscope, voltmeter, frequency meter. When the two systems are synchronized, the pointer on the synchrosope is stationary and points straight up.

What about DISTANT power plants?

- Electricity travels at almost the speed of light = 300,000 km/s
- So travel time across U.S. is about 1/100 of a second

1) Per IEEE Standards C50.12 and C50.13

http://en.wikipedia.org/wiki/Synchronization_%28alternating_current%29

Oops! *1/100 th of a second is almost one full 60 Hz cycle*

Thus AC phase from a distant power plant could be shifted by a lot more than 10° !

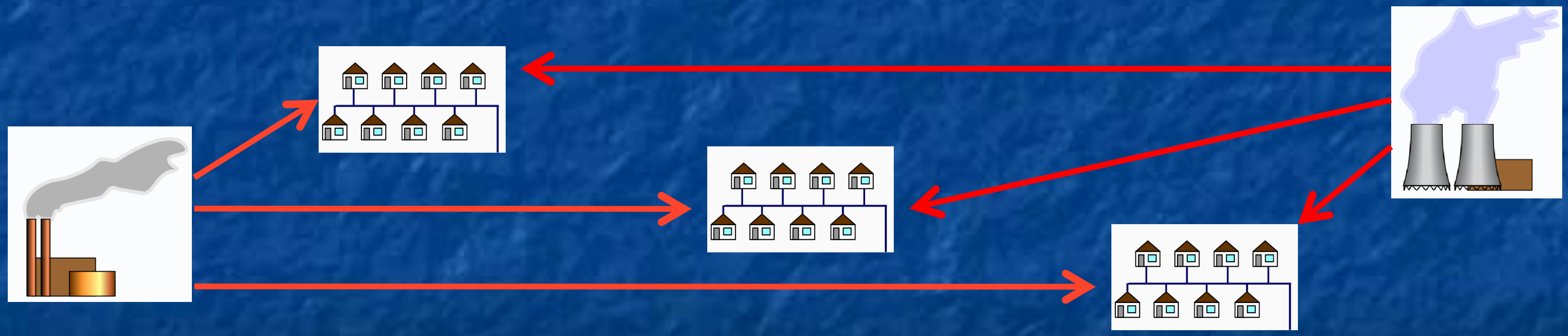
If that distant power plant serves only your town, there's an easy solution:

Have that distant power plant shift the phase of its AC generators

to compensate for the phase shift occurring during transmission

But your town is almost certainly **not** the only customer of those two power plants

Power plants send power all over the grid, over routes of all different lengths:



So on the scale of the US, it's impossible to match AC phase over all possible routes!

But long distance phase matching ends up being almost moot

Because you can't (efficiently) transmit AC power across the US anyway!

Due to another strange consequence of magnetic induction

Called **reactive power** - which produces the **stability limit**

And it goes to the question of:

ARE MAGNETIC FIELDS REAL?

That is: Are they just a manmade mathematical abstraction used to infer forces?

Or do they really have a sort independent existence?

To answer (and explain reactive power), we can no longer avoid Maxwell's Equations

I've tried to buffer you from them, but here they are:

Maxwell's Equations:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

They relate **Magnetic Field (B)** and **Electric Field (E)** to things such as

ρ = The amount (density) of net charge at a given location AND

J = The amount (density) of net charge flow at that location

From which we get things like Lenz's Law (our electro-magnetism Hand Rule)

Take a deep breath and bear with me:

In deep outer space there is almost zero charge, and zero charge flow

ρ and **J** thus fall to zero and Maxwell's equations become:

$$\nabla \cdot \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

But despite vacuum's lack of charge & charge flow, everything has NOT fallen to zero

In fact, the last two equations now seem to be saying:

The Electric Field is proportional to the Magnetic Field's rate of change

The Magnetic Field is proportional to the Electric Field's rate of change

But out in the vacuum of space, how could B and E continue to exist?

BY BOTH OSCILLATING (one out of phase with the other)

Then: Collapse of a **Magnetic Field** => Growth of **Electric Field**

Until magnetic field falls to zero, and electric field maxes out

And: Collapse of an **Electric Field** => Growth of **Magnetic Field**

And then cycle repeats over and over and over

Science fiction? No it's a weird phenomenon . . . that we call "LIGHT"

Light is STARTED by movement of charges, but it can then propagate for VAST distances ("light years!") in the complete absence of charges

So B and E fields ARE real: They exist and can even propagate on their own

And they can store and carry very real energy!

Applying this to our lowly wire coil:

When we connect a battery, it drives current (charge flow) through the coil

Part of the battery's energy goes into generating a magnetic field

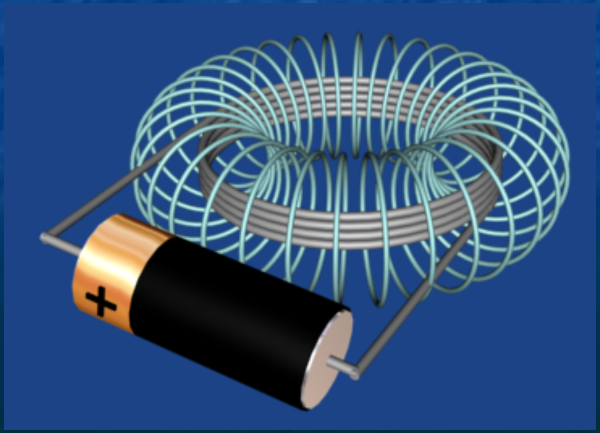
Which we represent as loops (around the path of the current)

These loops act sort of like rubber bands (storing energy in their stretch!)

When battery is disconnected, unsupported stretch of bands leads them to collapse

But in doing so they briefly push current/voltage backward

This pushback can be so intense and quick that it produces sparks!



Using this to expand our water flow analogy of electrical current:

Imagine we first connected a long **metal pipe** to a faucet:

We then turn on the faucet, applying water pressure to the left end, initiating flow:

If we then disconnected the faucet? Flow just stops (boring!)

If we leave the faucet on? Water (flow & pressure) eventually comes out right end:

This is the old, pre-magnetic field, analogy to electrical current flow

The new improved (magnetic field incorporating) analogy:

Our pipe is now made of highly stretchable rubber (it's become a hose):

We turn on the faucet, applying water pressure to left end:

ONLY PART of the water STARTS flowing down the pipe

OTHER PART "induces" a growing bulge in the hose's wall!

The energy stored in the stretched out rubber wall is analogous

to the energy stored in the induced magnetic field loops

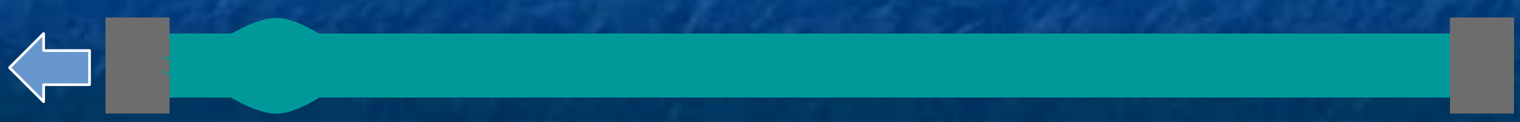
And if we then quickly disconnected the faucet?

Before turning the faucet off:

Immediately after disconnecting the faucet:

Propelled by the stretched out rubber, water shoots back in our face!!

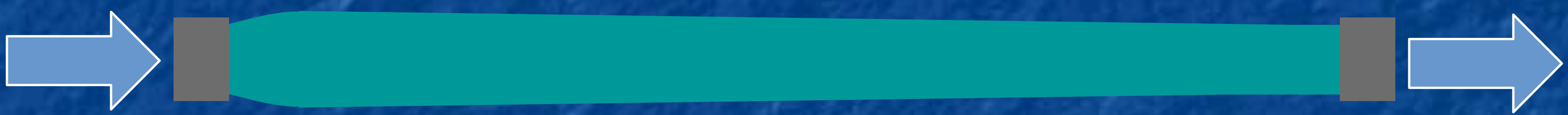
And this continues until the bulge fully relaxes:



What if we'd instead left the faucet connected?

Shortly after the faucet was connected and turned on:

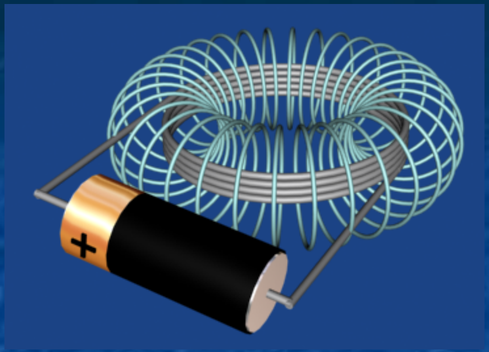
Later: Bulge has spread out, whole hose has slightly expanded due to pressure:



And if we THEN disconnect from faucet?

Contracting to original diameter, pulse of water is expelled from both ends

Our coil's behavior based on this enhanced water analogy:



After connecting battery, the initial charge flow is LOWER then expected:

Energy is being diverted into building up a magnetic field (rubber bands/hose)

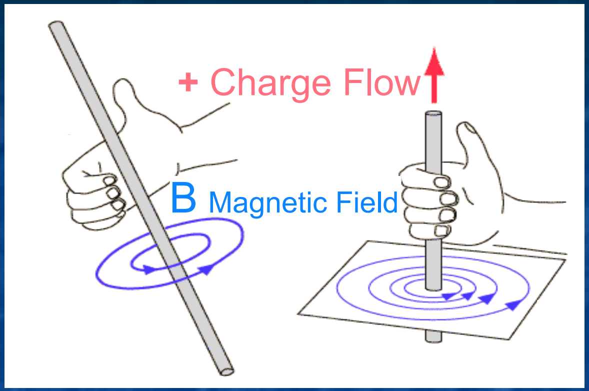
But if we leave the battery connected, charge flow rises to expected level:

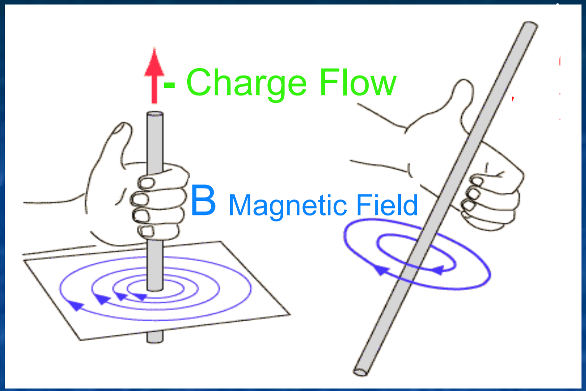
After magnetic field has been built up all along coil (stretched out rubber)

If at any point we disconnect the battery:

Charge briefly continues to shoot out the ends (due to contracting rubber)

Does this ONLY apply to coils?



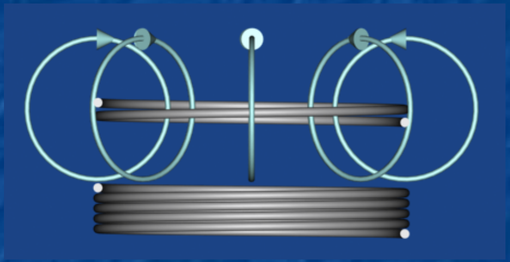


Lenz's Law Hand Rule says magnetic field forms around ANY charge flow

So why aren't same effects seen with straight wires?

They are seen, but they are much much weaker

Because magnetic fields are not gathered together:



But rubber-band-like effects become noticeable in LONG straight wires

Which is exactly what electrical power transmission lines are!

So in long power transmission lines:

When we first apply a voltage (as in the start of an AC wave cycle):

Current (charge flow) in the wire builds up more slowly than expected

Because part of the driving energy is diverted to build up Magnetic Field

Acting like the growing bulge in our rubber hose

When applied voltage reaches maximum (as at the peak of an AC wave):

The energy diverted to build up of the Magnetic Field diminishes

Leaving more energy to push the electrons

And the growth of the current flow catches up

When applied voltage again falls to zero (at the end of an AC half cycle):

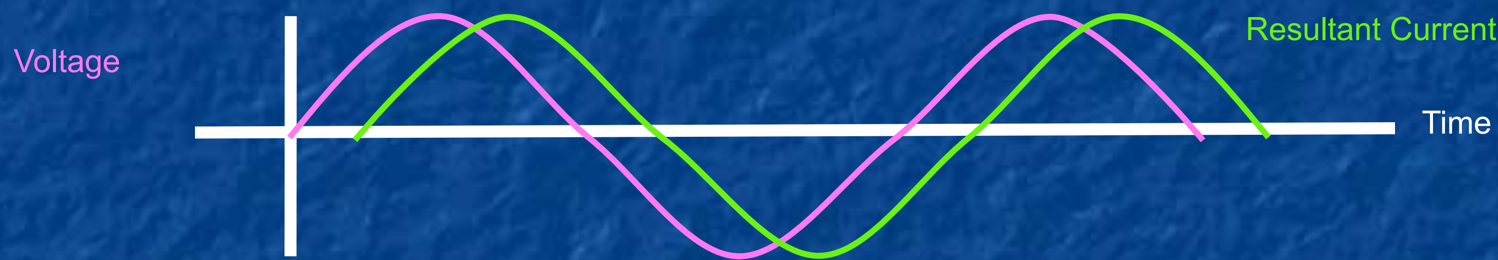
We expect the current flow to also fall to zero – but it doesn't!

As collapsing magnetic field continues to push electrons for awhile

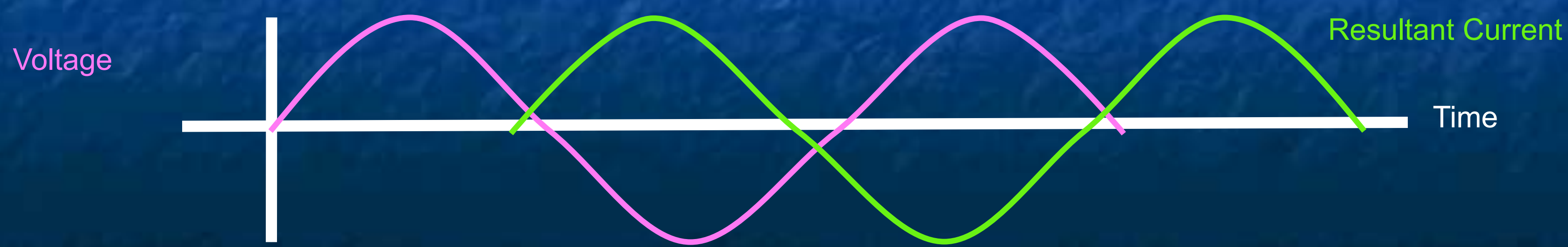
Thus, exiting a long AC transmission line, current falls behind voltage:

What we expect – before taking induced magnetic fields into account:

But out the end of a moderately long AC transmission line we actually get:



And out the end of a very long AC transmission line we get:



Weirdly interesting (perhaps), but why is this significant?

Specifically:

How does this kill the efficiency of long distance AC power transmission?

To answer, evaluate the power coming out the END of that power line

Employing the **water flow analogy**:

To do work I need not only water **pressure** but also water **flow**

Pressure with no flow will give you nothing, as will flow with no pressure

So for water: Delivered water power (at a given time) = Pressure (t) x Flow (t)

Similarly: Delivered electrical power (at a given time) = Voltage (t) x Current (t)

Working out electrical power with and w/o magnetic induction:

If Current stayed in sync with Voltage :

But for Current lagging behind Voltage:

Voltage (V):

Current (I):

Power = V I (falling to zero when EITHER V or I are zero):

We get far less power out when we account for induced magnetic fields!

*But why is this only a problem for **only** AC power transmission?*

Wouldn't there also be a current lag when you first applied a DC voltage?

And wouldn't current also flow for awhile after removing that DC voltage?

"Yes" to both questions (due to the same magnetic induction effects)

However: You don't turn DC voltage **on** very often, or turn it **off** very often

Soon after DC is turned on, current flow catches up and reaches its max

So DC **voltage** is then high at same time that DC **current** is high

Which gives you maximum possible power out

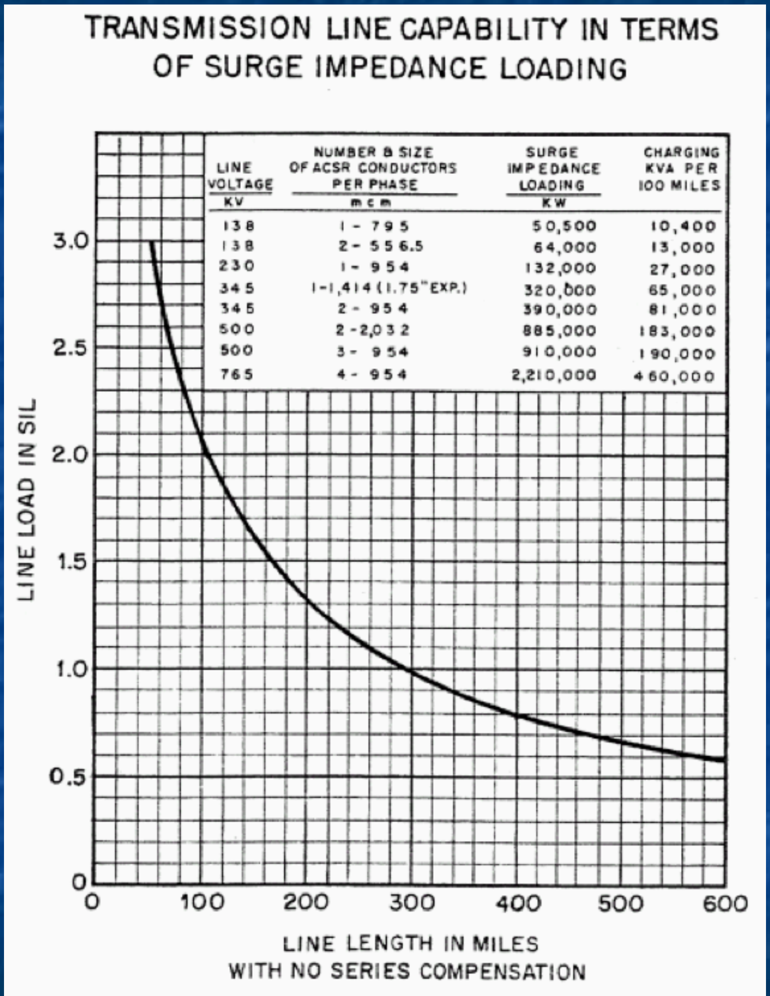
The problem with AC is that it is <u>always</u> turning on and off!

So AC current flow never manages to catch up to AC voltage

And you do NOT get maximum possible power out

And things get worse the longer the wire gets

Leading to a figure I dug up from the American Electric Power Corp.:



Which essentially plots:

AC Power Out vs. Power Line Length

Note how fast the output power falls:

It plummets in a FEW HUNDRED MILES!

All due to the AC voltage and AC current

getting more and more out of step

at the far end of a long power line!

Source: "American Electric Power – Transmission Facts"

Original link has disappeared but a cached copy is available on this note set's Resources Webpage

So AC power transmission is limited by TWO effects:

1) **Flowing electron current knocking into atoms, heating them up =>**

"Resistive power loss" (or **"thermal limit"**)

"Loss" because electrical power is **lost** by its conversion to heat

2) **Current flow lagging behind the applied (pushing) voltage =>**

"Reactive power" (or **"stability limit"**)

This is not so much a true **loss**, but more like a worsening **clog**!

You just can't force as much electrical power **through** longer power lines!

In comparison, DC power transmission

also suffers from the 1st effect – but NOT from the 2nd effect

Thus HV DC power transmission = Key to an efficient long distance grid:

HV (high voltage): Minimizes 1st limitation by reducing necessary current flows

DC (direct current): Eliminates 2nd limitation by eliminating magnetic induction

Which stems from ever **varying** (growing and contracting) magnetic fields

But this produces a couple of dilemmas:

1) >95% of power plants **like to produce** AC power (from spinning things)

2) 100% of our homes and businesses are set up to **use** AC power

The solution requires AC to DC conversion, then DC to AC back-conversion

Classically facilitated by TRANSFORMERS, DIODES & CAPACITORS

The following DOES get technical

Skim through it if you must

But if you've studied the preceding pair of Electricity & Magnetism note sets,

you've already "paid your dues"

and the following should now make sense

Further, the following not only describes some neat applications of "E&M"

it also provides a primer on "diodes"

which we will study later . . . as "photovoltaic solar cells"

and a primer on "capacitors"

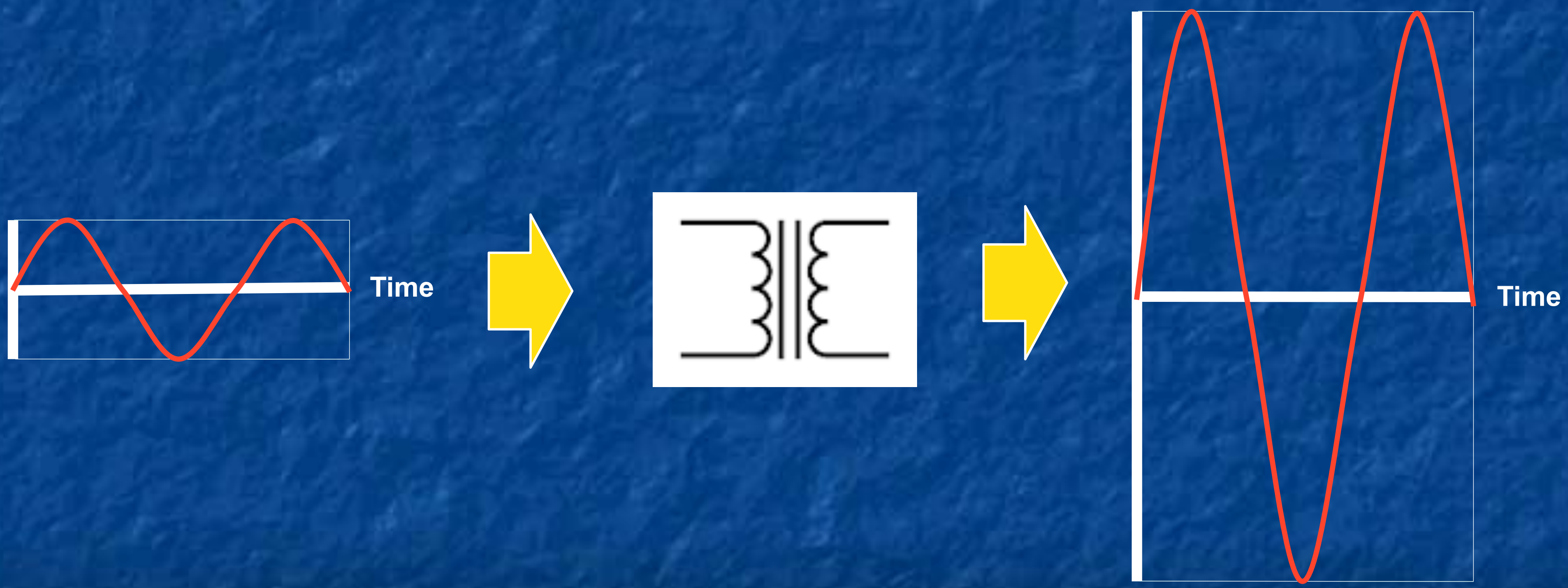
which may provide one of our best ways of storing Grid electrical energy

So don't sell yourself short (I don't) – Give it a try!

Conversion of AC to DC, and then back again:

Step 1) Convert power plant AC to higher voltage AC with transformer

Input: Medium voltage AC: Transformer: Output: High voltage AC:



Higher voltage out means lower current flow => Lower resistive loss

*For the next step, we need a new device: a **diode***

Diodes act like one-way doors to electrical current

Passing current flow in one direction

But blocking current trying to flow in the other direction

Textbooks seem to believe only electrical engineers can comprehend diodes

But I think we can **all** understand them

We've just got to learn about special materials called **semiconductors**

Semiconductors are called that because they are almost insulators

Insulator's electrons **all** remain bound to atoms (= why they don't conduct!)

But atoms retaining **all** of their electrons are neutral

So we can represent pure semiconductor material as boring gray:

The trick with semiconductors is to add special impurities:

The preceding base semiconductor sets the bonding rules:

If it's silicon (as it most commonly is), atoms of the crystal must have for bonds

Add some impurities with five valence electrons (e.g. Phosphorus or Arsenic):

Just a little! Say a part per million to a part per thousand

If one of them gets in a crystalline site, it will have an unused valence electron

Which can then break loose to wander, carrying its negative charge

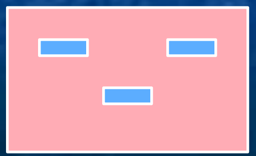
But that will leave the parent donor impurity short of an electron

Which will give that now fixed-in-place donor a positive charge

Which can be represented as this:

A background of stationary donor impurities

Plus their now wandering extra electrons



Or instead add another sort of impurity:

Ones with only 3 valence electrons (e.g., Boron):

Again, just a little: A part per million to a part per thousand!

If one of them gets in a crystalline site, it will lack a bonding / valence **electron**

But it can steal an electron from a neighboring silicon atom

Thus completing ITS 4 bonds to the crystal

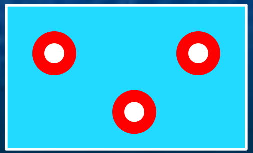
Leading it to be named an **acceptor impurity** (i.e., thief)

The victimized Si can then take an electron from its silicon neighbor

With that neighbor then taking an electron from its neighbor . . .

The now moving electron-deficient-bond, called a **hole**, carries a positive charge

All of which we can represent as this:



A background of stationary ionized acceptor impurities

Plus the now wandering positive holes

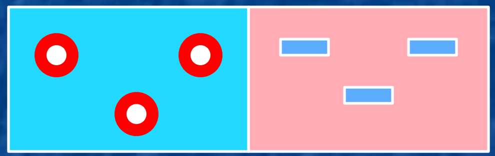
*Now build a semiconductor junction = a **DIODE***

By using two (generally flat) layers of semiconductor

One layer with added acceptor impurities

The other layer with added donor impurities

Giving this (when viewed from the side via X-ray vision):



Left:

Fixed negative background of now ionized acceptor impurities

+

The resulting wandering electron-deficient and thus positive holes

Right:

Fixed positive background of now ionized donor impurities

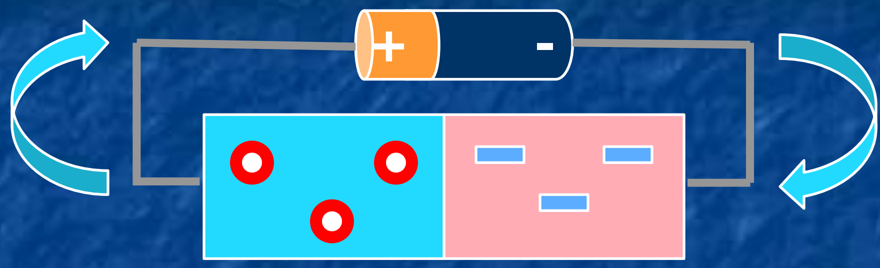
+

Their now liberated and wandering negative electrons

Finally, connect this to a battery and see what happens:

Apply voltage in one direction and current flows just fine:

Electrons are pulled out, making NEW holes at this end



While new are electrons pushed into this end

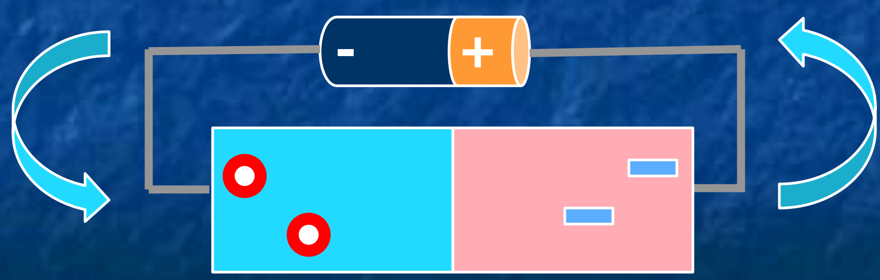
What's lost in one place is replaced at another!

At the center "junction:

Electrons pushed across **fill in** holes on the other side (both being replaced by new ones added at the ends)

But apply the voltage in other direction and current flow soon grinds to a halt:

Electrons are pushed in, filling up holes at this end!



Electrons are sucked out at this end!

Nothing is left to conduct current thru the center!

Nothing is replaced! Nothing is left to flow!

You may now owe yourself a big pat on the back

Because if you stayed with me over the last four slides:

You now understand something (diodes)

no longer understood by many/most electrical engineering majors

and long since forgotten by many (most?) EE professors!

(Test them and you'll see!)

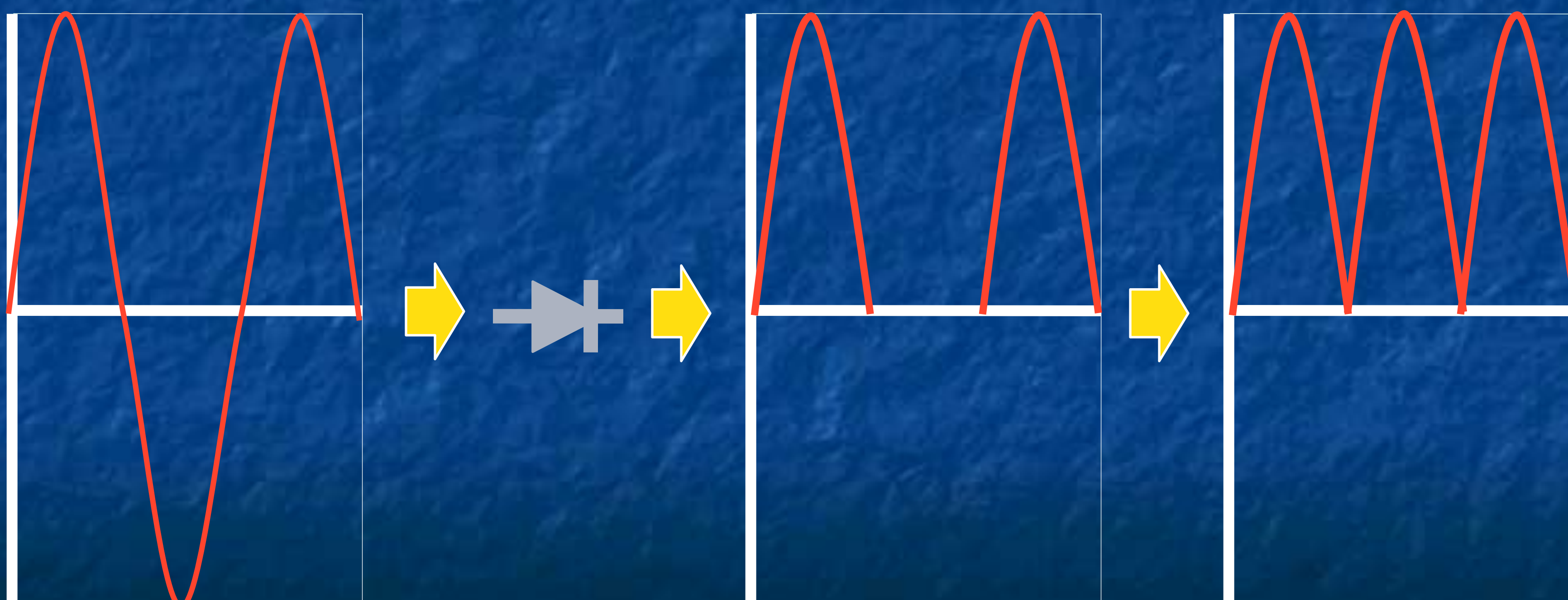
(We CAN Figure This Out!)

These DIODES facilitate the second step in AC to DC conversion:

Step 2) "Rectify" the high voltage AC using a "Diode"

For which the symbol is:  (symbol points in the direction current **can** flow)

HV AC in: | Diode: | Rectified AC: | Or via 4 diodes and a simple circuit:



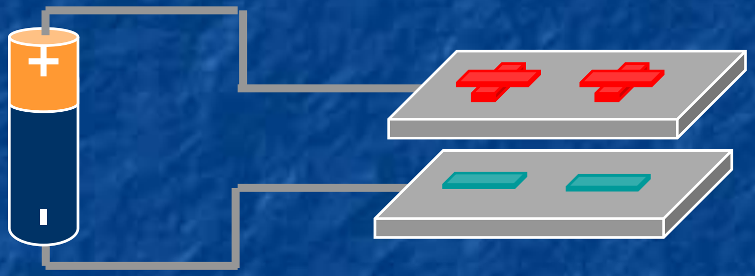
An Introduction to Sustainable Energy Systems: WeCanFigureThisOut.org/ENERGY/Energy_home.htm

For the next step, we again need a new device: a "capacitor"

Capacitors temporarily store charge => Smoothing out swings in voltage

This doesn't work because positives push on each other (as do negatives):

But fold it over and, if the two plates are close enough, **this does work**:



Because if plates are close enough, repulsion of like charges on one plate

is effectively canceled by their attraction to opposite charges on other plate

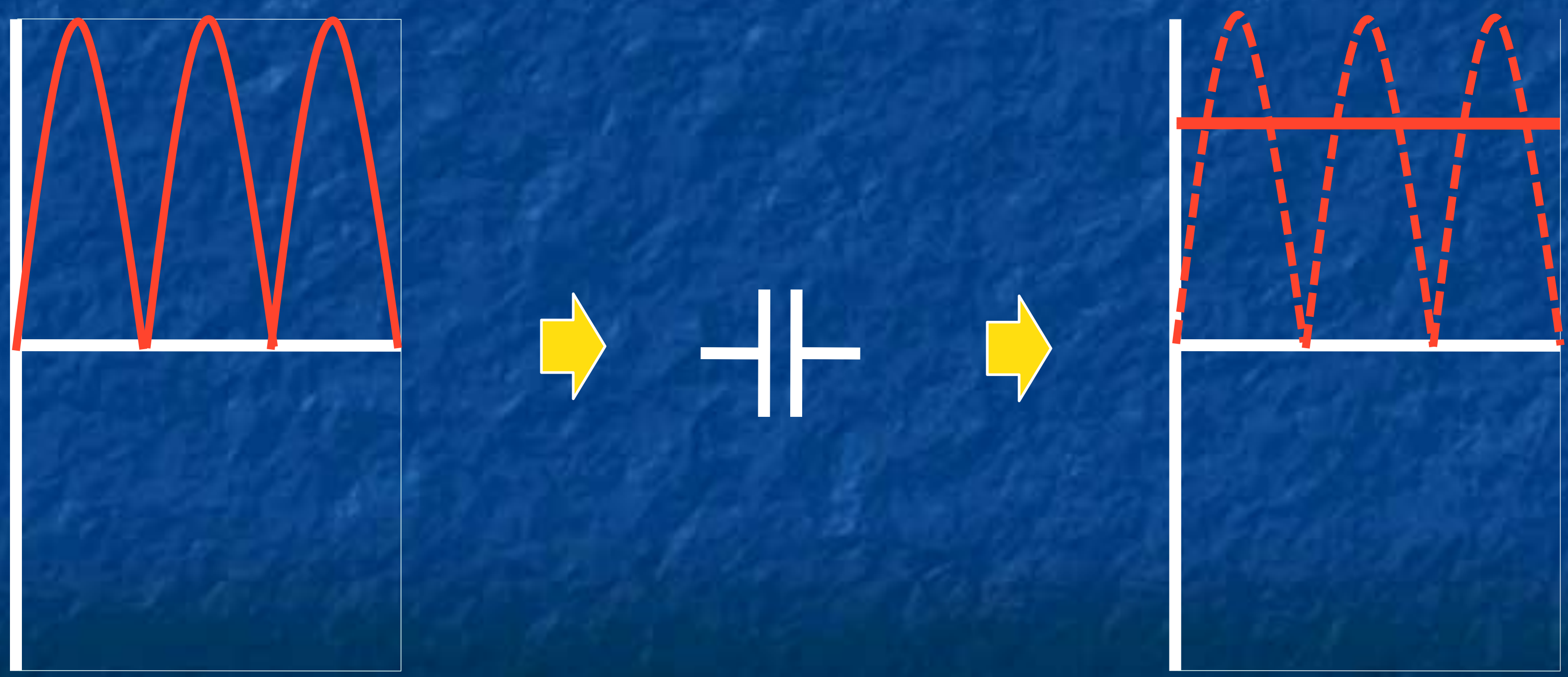
Which facilitates the third step in AC to DC conversion:

Step 3) Smooth rectified AC into DC via a "Capacitor"

The "capacitor" symbol is just: 

Capacitor temporarily stores charge => Smoothing by shifting peaks to valleys

Rectified HVAC in: Capacitor: High Voltage DC:



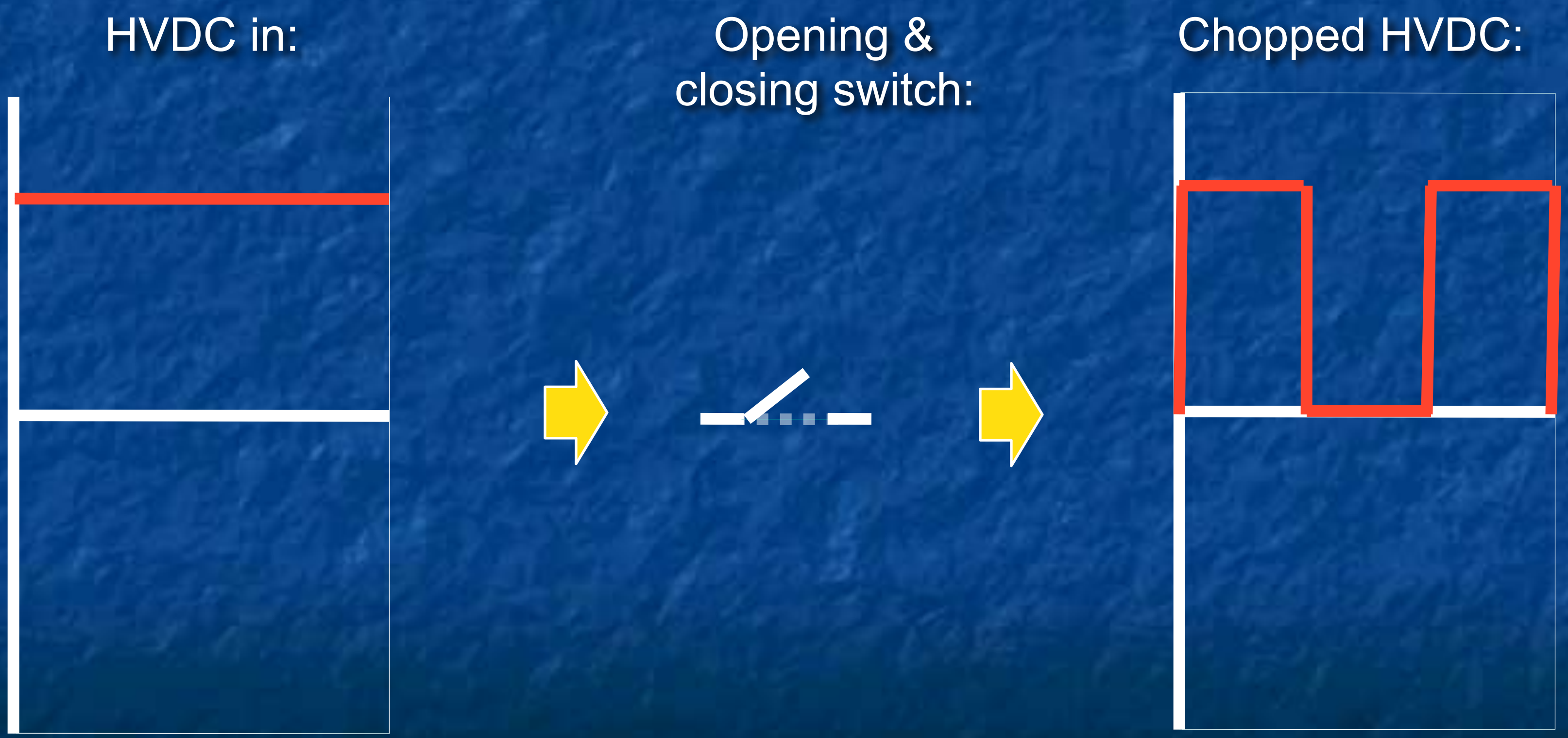
Which is now ready to be sent down a long power transmission line!

At the other end of that power line we need an on-off switch:

With which we'll start the conversion of DC back into AC

Step 4: "Chop" the DC power

By sending it through an opening and closing switch: 



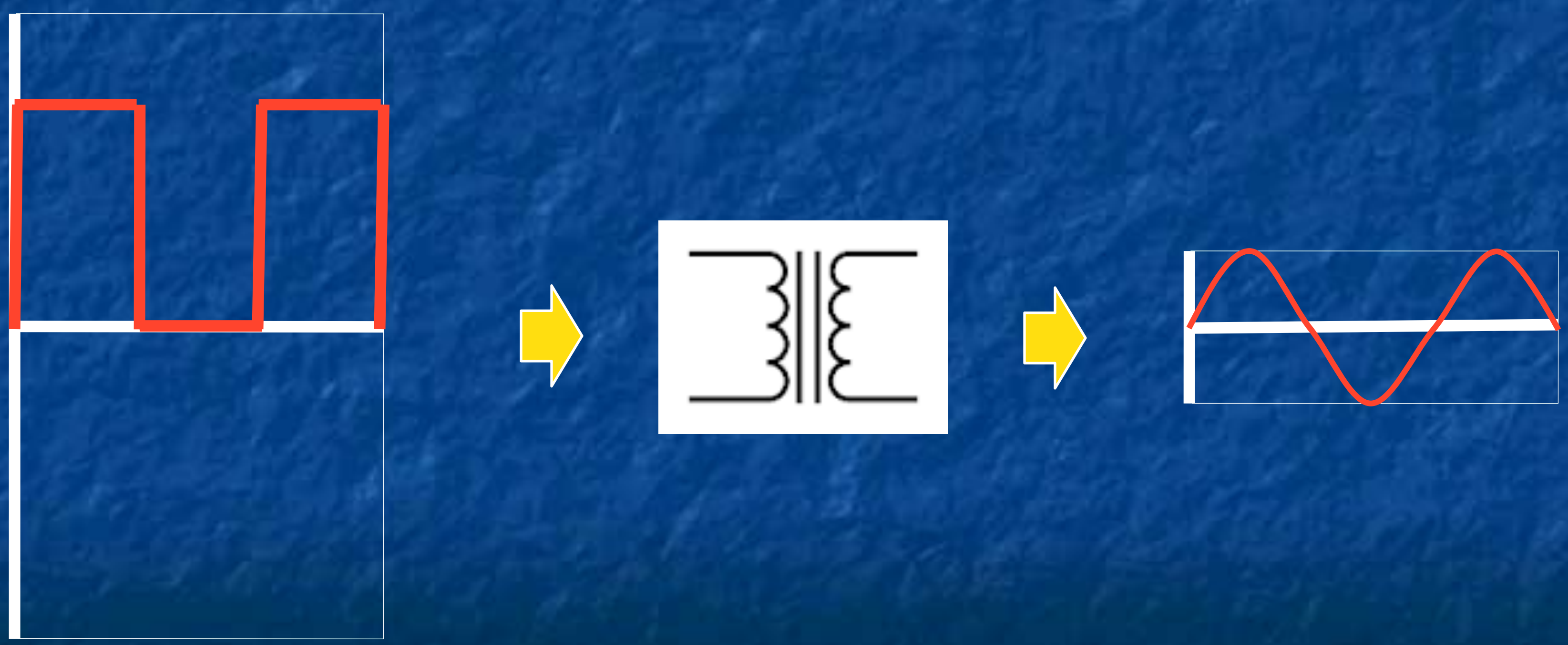
This "chopped" DC now acts sort of like AC, facilitating next step:

For the final step we are back to transformers:

Step 5: Smooth and transform "chopped" HVDC back into into AC

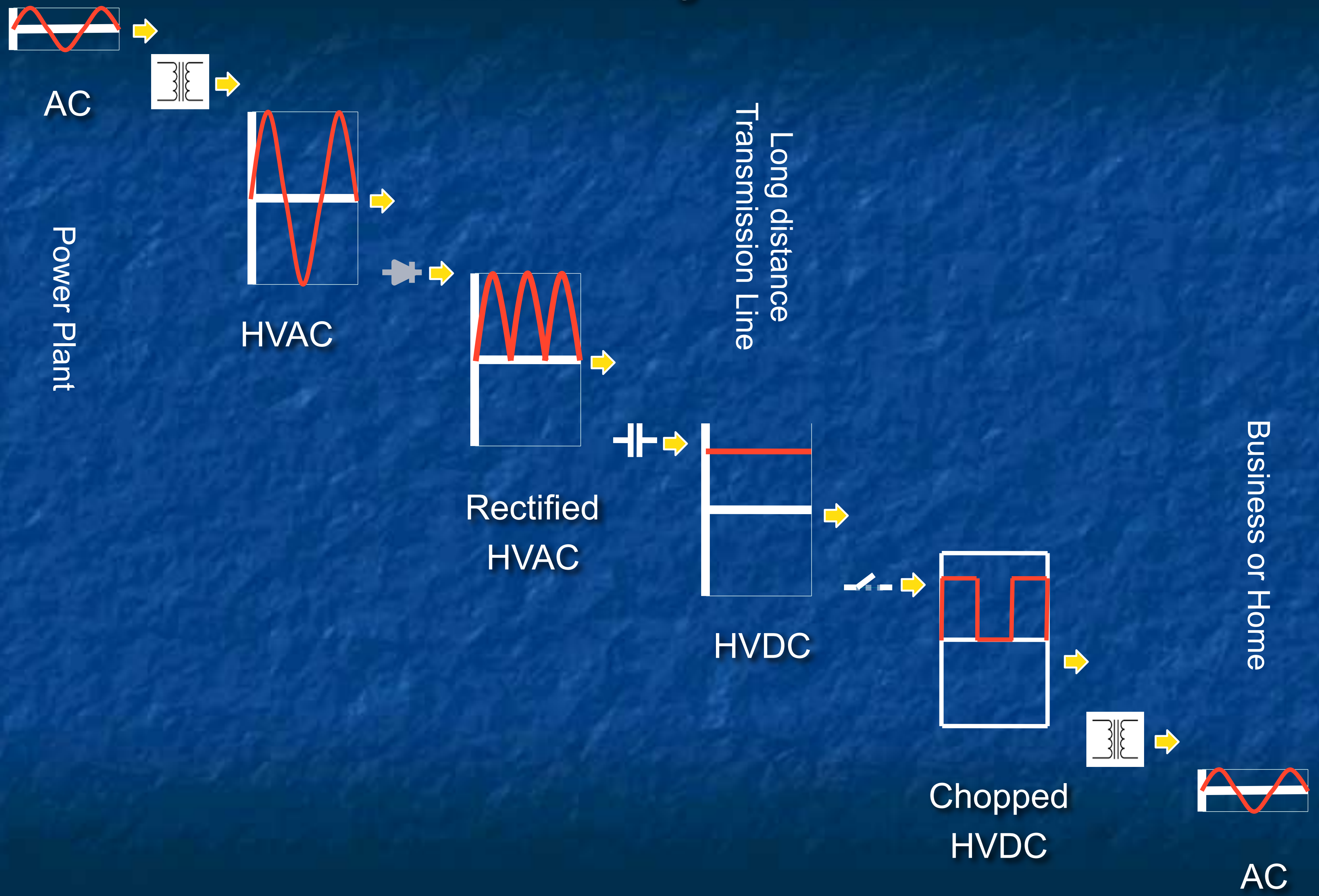
Transformer works on chopped DC because its ups and downs mimic AC:

Chopped HVDC in: Transformer: Low Voltage AC:



Ready to be sent to your neighborhood!

Summarizing all of that:



That clearly wasn't easy!

As a result, high voltage DC transmission is still relatively rare

Despite low resistive losses + ability to transmit long distances

Complexity is **part** of the problem

But bigger barrier is cost/reliability of some of those conversion devices

Transformers are pretty simple and well developed

We are also pretty good at capacitors (= metal plates and gaps)

Switches are simple, but they can be eroded by inductive sparks

Diodes are not only difficult but they can be **killed** by inductive sparks

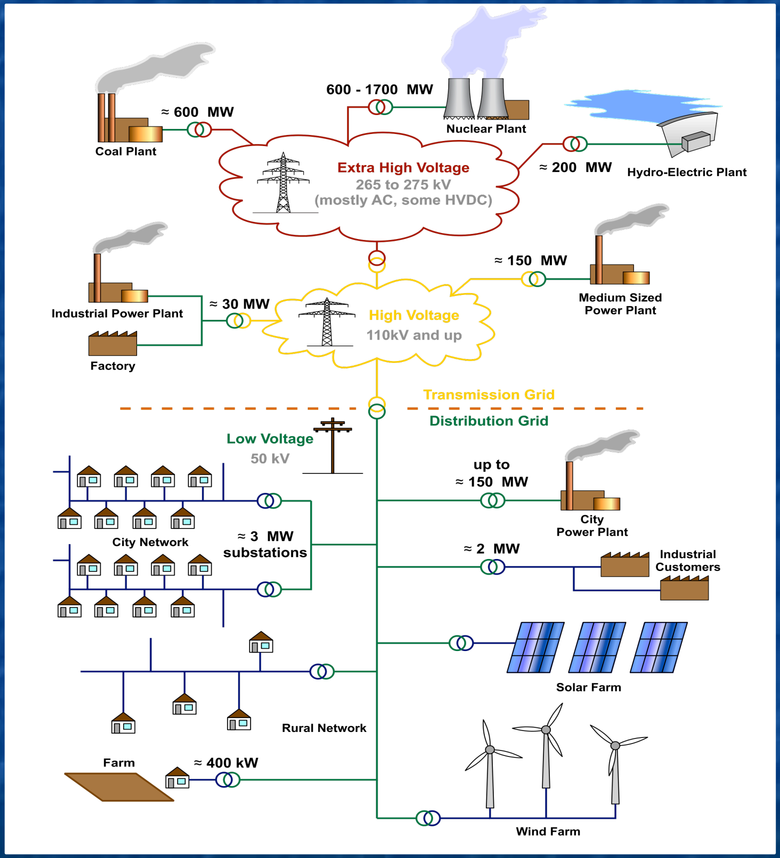
So, until recently, high voltage switches and diodes have been the bad actors

But both can now be made with new high voltage tolerant semiconductors

=> Far more recent interest in efficient, long distance, HVDC transmission!

= A rather complete overview of today's power plants and grid

TODAY's Grid still depends on high voltage **AC** (HV AC) for power transmission



But you've now also seen why:

Power could be sent much further

via high voltage DC (HV DC)

Which, as we'll see in later note sets,

will be ESSENTIAL if we are ever to

make heavy use of WIND & SUN power

Credits / Acknowledgements

Some materials used in this class were developed under a National Science Foundation "Research Initiation Grant in Engineering Education" (RIGEE).

Other materials, including the WeCanFigureThisOut.org "Virtual Lab" science education website, were developed under even earlier NSF "Course, Curriculum and Laboratory Improvement" (CCLI) and "Nanoscience Undergraduate Education" (NUE) awards.

This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.