A Renewable / Distributed Grid

John C. Bean

Outline

Characteristics of today's power plants and grid

Dealing with Wind & Solar's naturally Grid incompatible forms of electrical power:

- Wind's asynchronous AC power and Solar's DC power

Today's solution: Universal Power Converters

- Small versions of which now also charge the batteries of our personal devices

Opening the door to a 12/7 Renewable Grid

- Which, overnight, would leave you shivering or sweating in the dark

The additional elements required for a 24/7 Renewable Grid?

- Massive Energy Storage: To save daylight/wind energy for overnight use
- High Voltage DC Electrical Power Transmission:
  - Allowing generation of renewable energy in the most advantageous locations
  - But consumption of that energy where we most want/need it

(Written / Revised: November 2019)

A Renewable / Distributed Grid

As described in my note set **A Generic Power Plant and Grid** (pptx / pdf / key):

We typically get most of our power from a single, large, not too distant, power plant

In 80% of such plants, electricity is produced by steam, driving a turbine generator

Represented as this:

But with turbines actually more like these:

The other ~ 20% of plants just substitute water flow for steam flow

With that water driving turbines like this:

Similarities between all of those present day power plants:

THEY ARE BIG:

Median size of modern turbine-generator based power plants is about 600 MW

With average U.S. power use per household at about 1.25 kW [1]

That means a typical U.S. power plant can power up to ½ million homes

THEY ARE NEARBY:

Made possible by the fact that **we bring the fuel to the power plant**

Via coal trains, gas pipelines, oil pipelines, or trucks bearing fuel rods

Saving us the trouble, and inefficiencies, of long distance power transmission

1) http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

Power plant similarities (continued):

WE CONTROL THE FLOWS DRIVING SUCH PLANTS:

For the 80% of plants using steam:

We control the **heat** sources that generate that steam

For most of the remaining 20% of U.S. power plants (using hydroelectric dams):

We control the water flow

ALLOWING US TO SYNCHRONIZE THE ROTATION OF GENERATORS

Aided by motor/generator effects that tend to draw their speeds together

We can thus produce AC power at:

60 Hz, within ~ 0.067 Hz, at phase differences within 1/36th of cycle

and 110 Volts, within 5% (again, see earlier "Grid" lecture for details

Most of this goes out the window in a renewable-based grid:

Because (as emphasized in both our textbook and my earlier lectures):

No single, simple, local, renewable energy source offers enough power

1) Which will compel use of smaller, or even downright small, power plants

"Smaller" including mixes of solar, wind, tidal . . . energy farms

"Downright small" including solar arrays on the roofs of individual homes

2) Many of which will NOT be nearby because to get enough renewable power

We'll have to move plants TO the best sunlight, wind, tidal . . . sources

3) And there we will not control the input flows

Because, instead, nature controls flows of solar, wind, tidal . . . energy

4) Result: Dispersed plants producing different voltages, currents & frequencies

Essentially: Electrical chaos (unless we do something about it!)

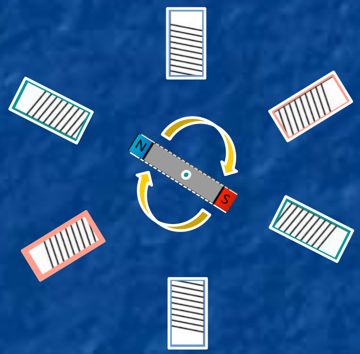
To illustrate the challenges, start by considering **wind** *power:*

For which uncontrolled wind flows are an immediate problem:

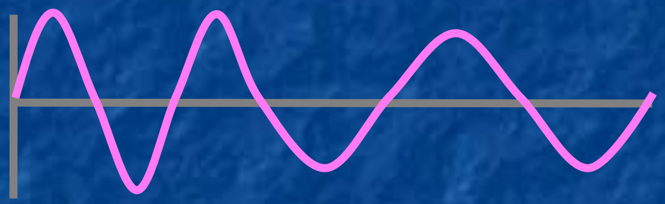
We've learned that wind speeds are highly variable

And wind turbines thus naturally turn at highly variable speeds

But if this rotation is passed directly to an electrical generator:



That generator will produce a highly variable AC output voltage:



And if wind turbine #1's voltage is high, when wind turbine #2's voltage is low,

they're going to shove power back forth, rather than working together

Early wind turbines dealt with this via "variable pitch" blades:

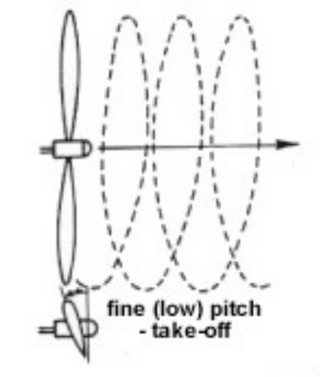
Which are also used (in reverse) on airplanes and ships

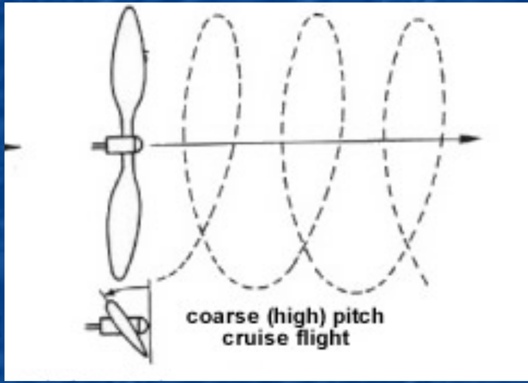
In variable pitch propellers, the angles of the propeller blades are changed

Here, so that an airplane engine operating at about the same speed can produce:

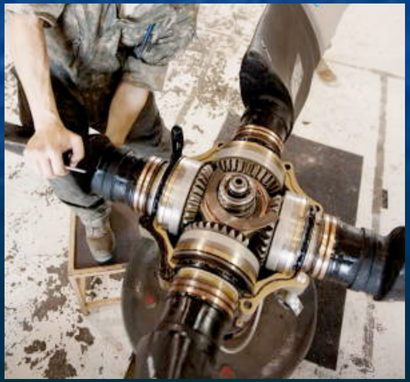
Lower speed takeoff airflows

Higher speed cruising airflows





All done via a fairly simple gear mechanism within the hub:

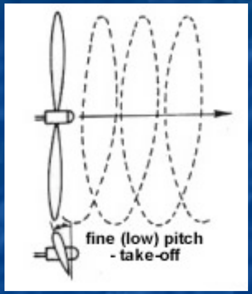


top figure: http://www.pilotfriend.com/training/flight_training/fxd_wing/props.htm

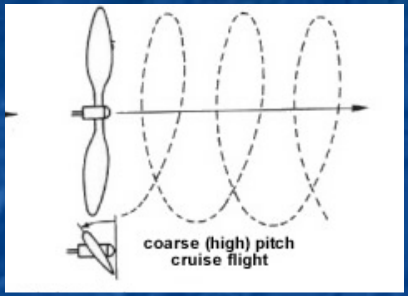
bottom figure: http://www.explainthatstuff.com/how-propellers-work.html

Turning this around for a wind turbine:

When wind speed is low,
flatten the blade angle:



When wind speed is high,
increase the blade angle:



Which will tend to keep the blade rotating at closer to a constant speed

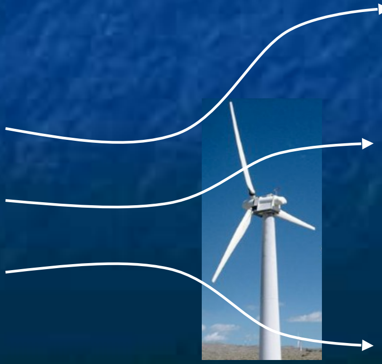
Which would work well for incompressible water, running thru a tunnel

But wind (air) is compressible, and it is not constrained to flow in a tunnel:

Flatten the blades too much and wind's going to go around the turbine!

This:

Becomes this:



Losing power!

So modern wind turbines do something different:

They DO still use variable pitch blades, but they use them to either:

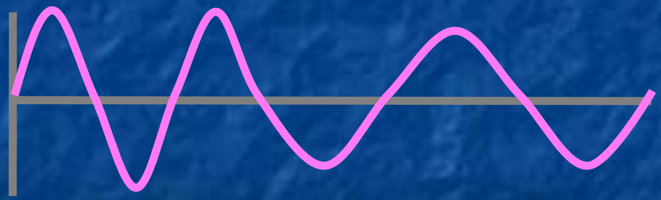
1) Maximize the energy extracted from the wind flow

Which generally requires changing blade pitch AND rotation speed

2) Avoid damage in extreme winds (by then "feathering" the blades)

Meaning that they essentially give up on keeping rotation speed constant!

RESULT: Modern wind turbine generators produce highly variable AC power



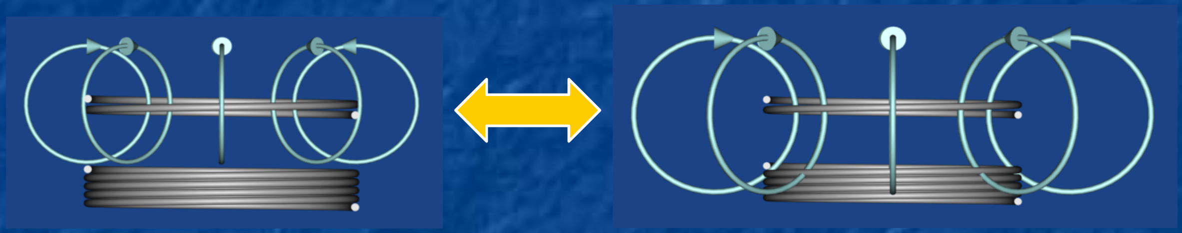
To correct this, some sort of power conversion circuit must be added!

Conversion has traditionally been based on ***transformers****:*

Which, as explained in my note set on Magnetic Induction (pptx / pdf / key):

Use pulsing electric current in one coil, to create pulsing magnetic fields,

Which sweep through a second coil inducing currents in it:



Power (voltage x current) flowing in one coil => Power (V x I) flowing out the other

But the voltage can be increased (or decreased) at the expense of current:

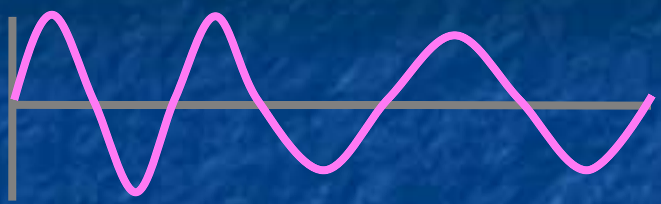
$\text{Voltage}_{in} \times \text{Current}_{in} = \text{Voltage}_{out} \times \text{Current}_{out}$ But:

$\text{Voltage}_{out} \times \text{Number coil turns}_{in} = \text{Voltage}_{in} \times \text{Number coil turns}_{out}$

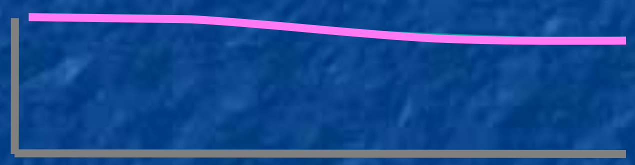
Ability to easily transform voltage is WHY AC power was chosen in the first place!

As applied to our wandering wind turbine's output:

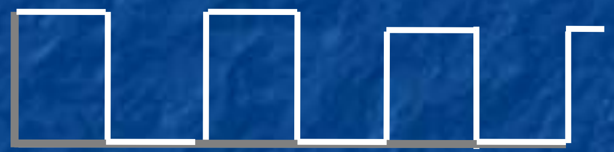
Raw wind turbine generator output, a 110 Volt-ish, 60 Hz-ish wobbly signal:



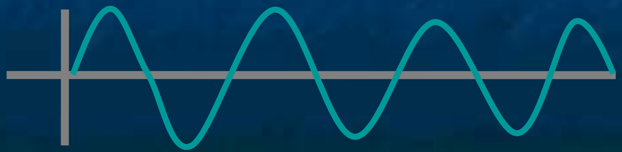
"Rectified" & smoothed into ~ DC (via the diodes & capacitors of my “Grid” lecture):



"Alternated" (chopped on/off with a switch) to make a 60 Hz square wave:

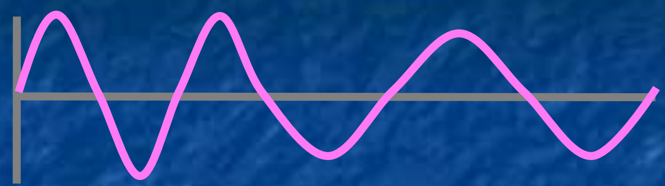


Then transformed and smoothed into ~ 110 Volt, 60 Hz AC:

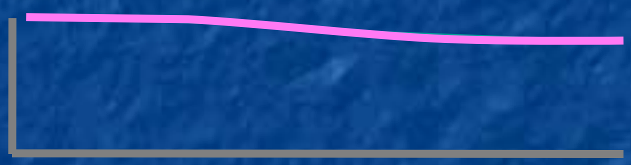


*But this didn't **quite** get us to our goal of constant 110 VAC power:*

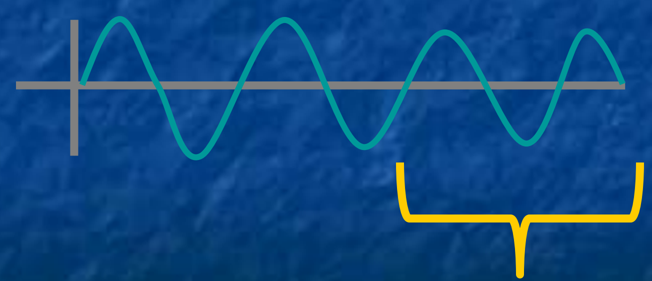
Raw wind turbine generator output varied in **both** amplitude and frequency:



We rectified out its natural oscillations, then added them back via 60 Hz chopping:



Which, via a transformer, then became almost constant 110 Volt 60 Hz AC:



But we really needed stronger transforming (to get to full 110 Volts) near end

It's similarly difficult to get constant 110 VAC from solar cells:

Solar "photovoltaic" cells naturally produce a trickle of near 1 Volt **DC** output

Determined by material's electron bond liberation energy (a.k.a. “bandgap”)

Variable sunlight compounds problem by producing major shifts in output current

Along with lesser shifts in output voltage

Now, solar cells **ARE** usually connected in "series" (i.e., connected nose to tail)

If you connect **enough** cells (about a hundred) you would get about 110 Volts out

But this would be still be a DC (i.e. approximately constant) voltage

And thus incompatible with our AC based grid

And it would still wander in voltage as sunlight intensity changed

So we again need some sort of power conversion circuit:

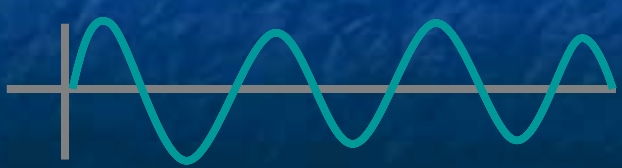
Solar cell power output conversion:

Raw output of single solar cell, a 1 Volt-ish, DC-ish signal:

Connected in series with ~ 100 other such cells:

"Alternated" (chopped on/off with a switch) to make a 60 Hz square wave:

Transformed into a 60 Hz, but again **not quite constant** 110 Volt amplitude wave:



This might almost work if we were "off the grid"

That is, if we were only generating home wind or solar power,

and only used that power for motors and heaters

But modern electronics (especially computers) demand near constant voltage

And would get very unhappy with our 110 Volt-ish, 60 Hz-ish home brew

Further, if we tried to **share** our power with neighbors,

or **supplement** our home power with Grid AC power:

Higher voltage power supplies would send power to lower voltage power supplies,

(with possibly catastrophic effects), rather than working together

So a modern renewable power grid requires ACTIVE power conversion

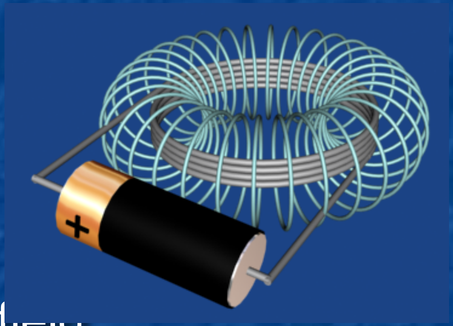
ACTIVE CONVERSION = Continuously monitored and tweaked conversion

Continuous ***monitoring*** *is done by modern integrated circuits*

But how do they then **control** the power conversion?

By using another magnetic phenomenon: **The energy stored in magnetic fields**

As also detailed in my note set **A Generic Power Plant and Grid** (pptx / pdf / key):



When we first connect a battery (or power supply) to a coil

It begins to "push" current through that coil

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

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

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

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

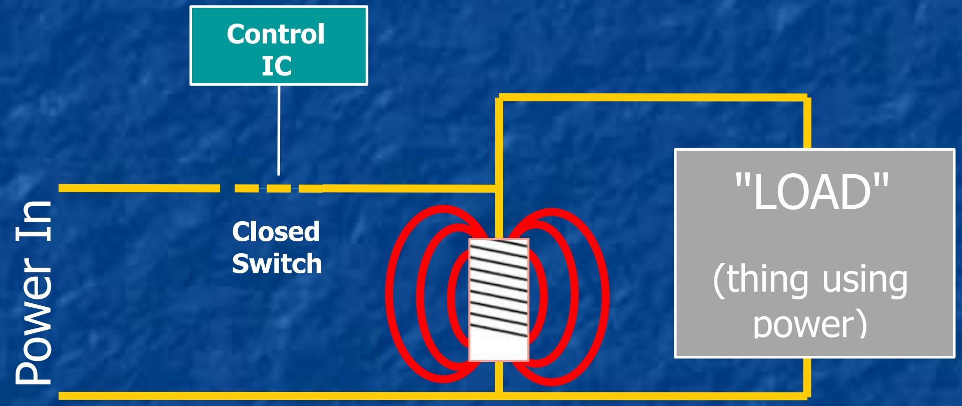
But in doing so they briefly push current/voltage **backward**

So now let an integrated circuit control current into a coil:

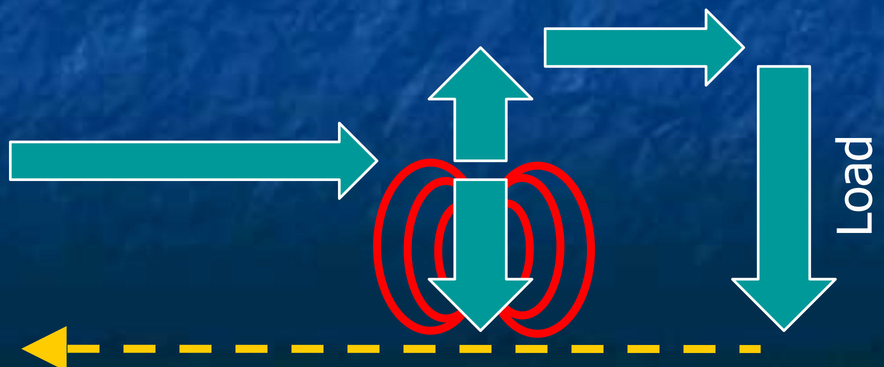
Bring DC power into the (simplified) circuit shown below

Controlling IC (integrated circuit) first closes the switch,

Allowing current to flow through BOTH coil (building up its magnetic field) and "load"



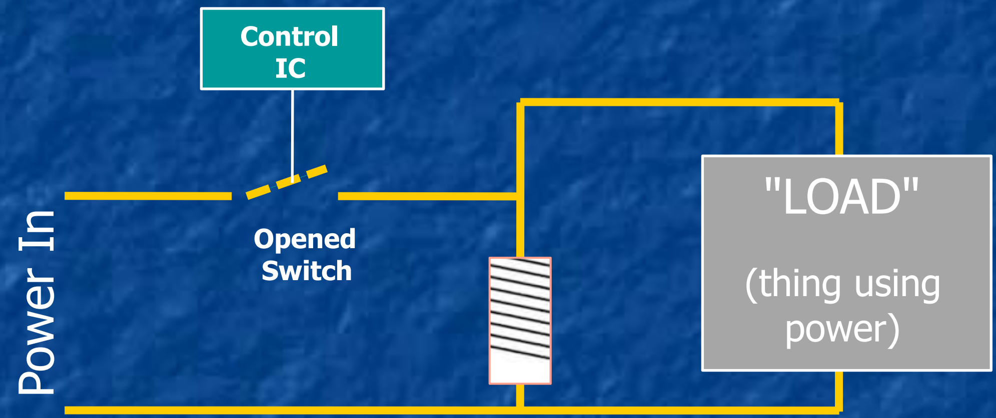
Current flow paths when switch is closed:



When time is right, control IC then opens up the switch

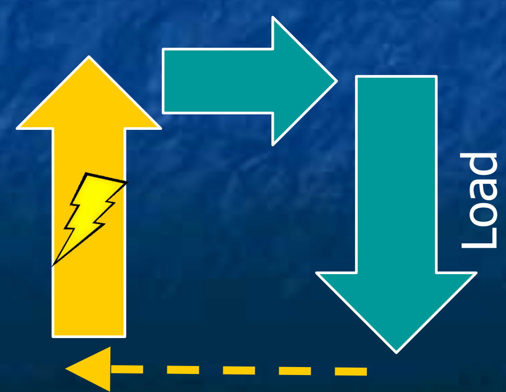
This stops incoming current – including part which had been going through the coil

Coil magnetic field then collapses, sending **BIG pulse of voltage backward**

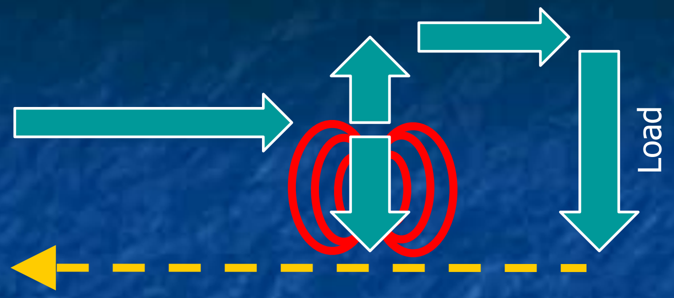


But only route through which voltage pulse can now drive current is thru the load!

NEW **higher** current flow path:



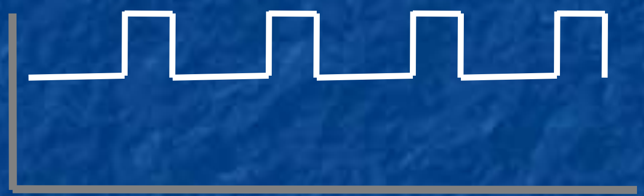
Current passed through load with switch closed AND opened:



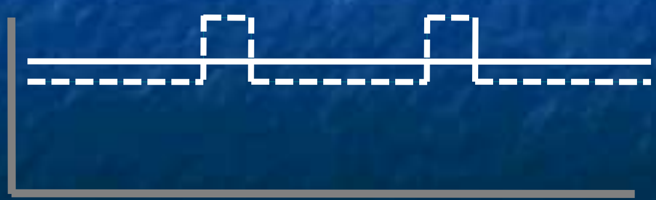
But current was **strongest** just after switch opened (due to magnetic field collapse)

IC controls **how often** switch opens, so power delivered to load can be varied:

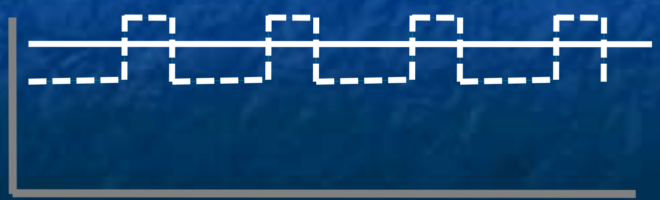
OR:



Add to the "load" a capacitor (which stores charge and averages current) to get:



OR:



So a specific, constant, output DC voltage can be "dialed in"

The IC doesn't care what the exact **input DC voltage** was

The IC will always adjust the switching to produce its target **DC output**

The load can be sent **higher** charge/voltage

OR with different IC programming, it can be sent **lower** charge/voltage

In some circuit variations, the IC can even cope with **input AC voltage**

And, by switching at appropriate cycle times, still produce **DC output**

Still other variations, can covert **AC to DC**, or **DC to AC**, **DC to other DC**

In other words, these smart IC + inductive coil based circuits can function as:

UNIVERSAL POWER CONVERTERS

These include the new chargers we use for all of our batteries!

Which, unlike the old chargers:

Are cool (i.e. far less wasteful of energy), small, and lightweight

And don't care about voltage or frequency of socket they are plugged into

The complete circuits are a **bit more complex** than I depicted (but not much!)

For an excellent tutorial explaining the basic DC to DC converters, see:

"DC-DC Converters: A Primer" - Jaycar Electronics

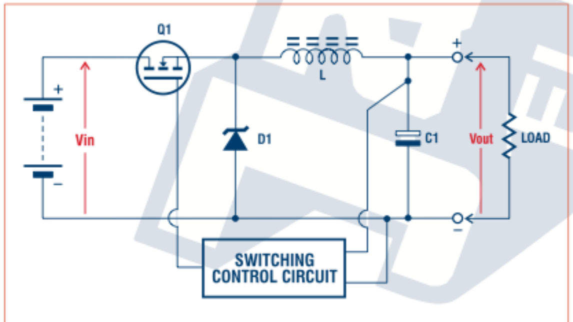
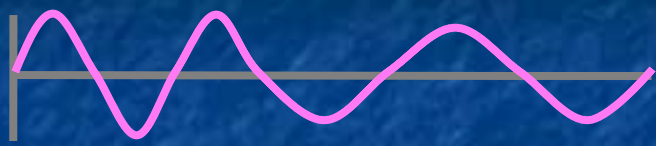


Fig.1: The basic circuit for a Buck type of DC-DC converter. How large Vout is as a proportion of Vin depends on the switching duty cycle for MOSFET Q1.

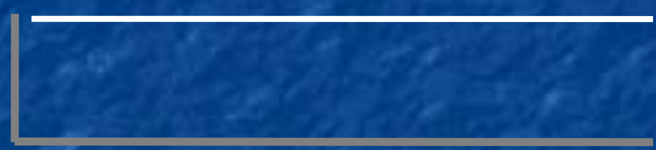
[My cached copy of now missing Jaycar web posting]

Variants can also solve problems with sloppy wind/solar power conversion:

Raw wind turbine generator output, a 110 Volt-ish, 60 Hz-ish wobbly signal:

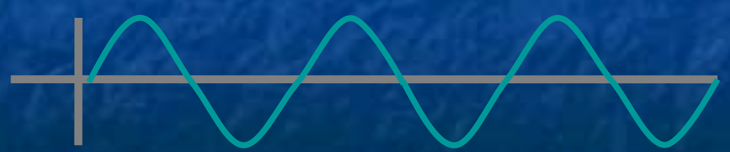


ACTIVE IC controlled conversion circuit can convert this to CONSTANT DC:



Open/closing **switch** then converts this to a constant amplitude 60 Hz square wave:

Which a **transformer** then smoothes into tightly controlled 110 Volt, 60 Hz AC:



In fact, conversion ***can*** *be even simpler:*

Integrated circuit controlled "switching" conversion circuits can do it all:

Largely, or even completely, eliminating transformers

Along with their shortcomings of heat, size, and weight

Versions can even be used for **HIGH VOLTAGE** power conversion

By using newer semiconductor materials,

that are better able to handle high voltages,

(which will come up to later in this lecture)

This solves the FIRST big challenge of renewable energy sources:

Their apparent incompatibility with the local 110 VAC grid

An important ramification: Bigger is no longer ***necessarily*** *better*

For over a century, the most efficient way to generate controlled AC power

has been BIG, CENTRALIZED POWER PLANTS (e.g., our 600 MW plants)

But larger **conversion circuits** are not necessarily cheaper or more efficient

In fact, because such conversion circuits still produce some waste heat,

Getting rid of that heat can be more difficult if they are supersized

Thus, in a renewable grid, the simplest most intrinsically efficient unit may be:

A **single** wind turbine with self-contained 110 VAC conversion OR

A **single** bank of solar cells with self-contained/local 110 VAC conversion

In fact, even in a **large** wind or solar farms:

Turbines & solar cell banks retain **individual** power conversion circuits

Instead of using a shared, centralized, single power conversion facility

If you WANT more power at that location, fine, install more units

But cost / unit installed will not necessarily drop in proportion to farm size

CONTRASTING with **fossil fuel** / **hydro** / **nuclear** / **geothermal** / **solar thermal**

Where economics of steam generation, turbines and re-condensation

Almost always produce much higher efficiencies in large plants

So you COULD own a personal **wind turbine,** if costs were low enough,

And if you accept that short turbines catch far less wind than tall turbines

OR if you could talk neighbors into a shared tall turbine

And you COULD consider buying your own personal **solar photovoltaic array**

If costs were low enough, and you have:

A BIG properly oriented roof or a HUGE yard

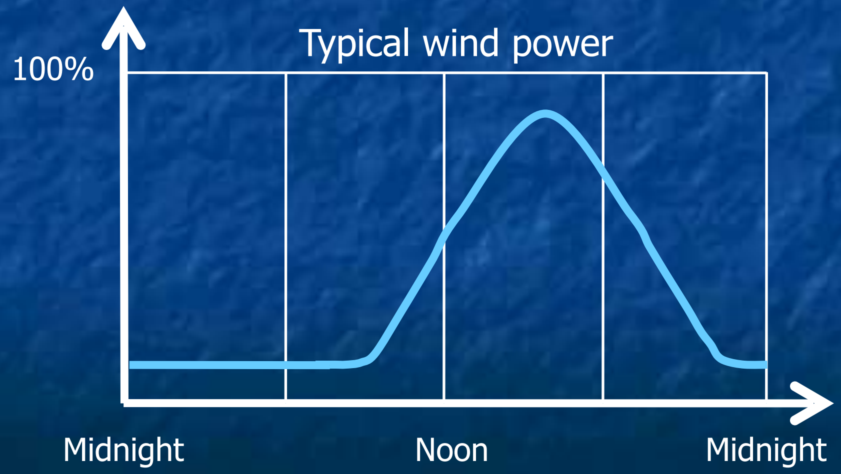
Because solar power is so dilute!

So where would we stand with such a "renewable" grid?

Well, at night we'd stand (or lay) in the dark and cold:

Because, from my note set **Power Cycles & Energy Storage** (pptx / pdf / key),

Wind and solar power cycle like this:



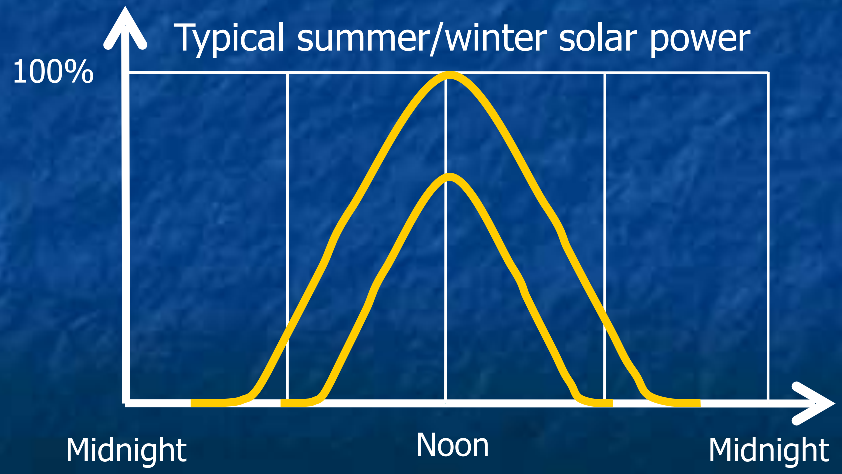


Photo: http://www.dailymail.co.uk/femail/article-1241772/Im-frozen-time-What-like-live-TVs-Victorian-Farm-electricity-running-water-outside-loo-5c.html

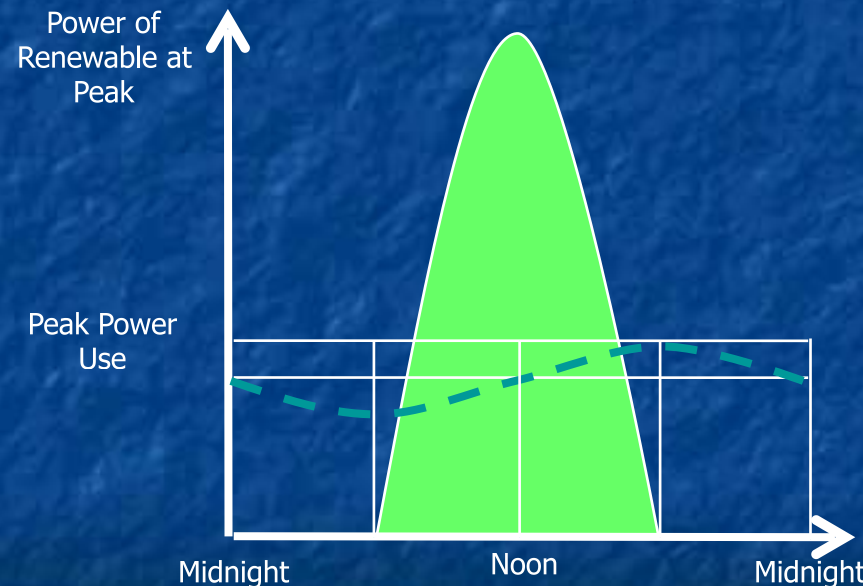
Power storage could eventually provide a solution

My lecture on that subject identified alternatives including:

Pumped storage hydro, super-capacitors, super-batteries & molten salts

But those now offer **nowhere near** the affordable storage capacity we would need

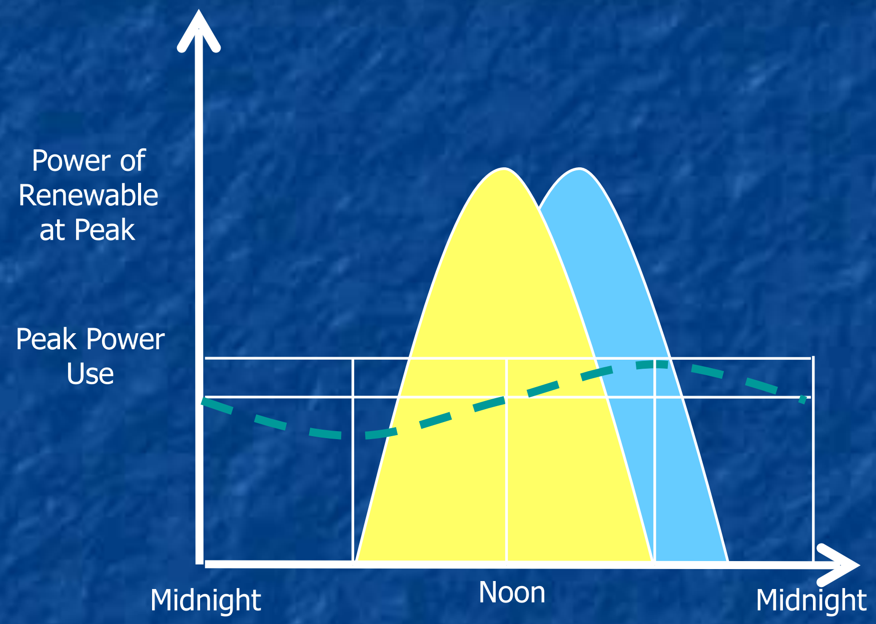
Especially if we try to "level out" power from a **single** renewable source:



We've got to shift enough power from the peak to fill in the blanks on both sides!

A somewhat limp partial solution: Use two different renewables

For instance: Solar (peaking at noon) + Wind (peaking in mid/late afternoon):



Trying to fill in blank spots to left and right by doing a "eyeball integration:"

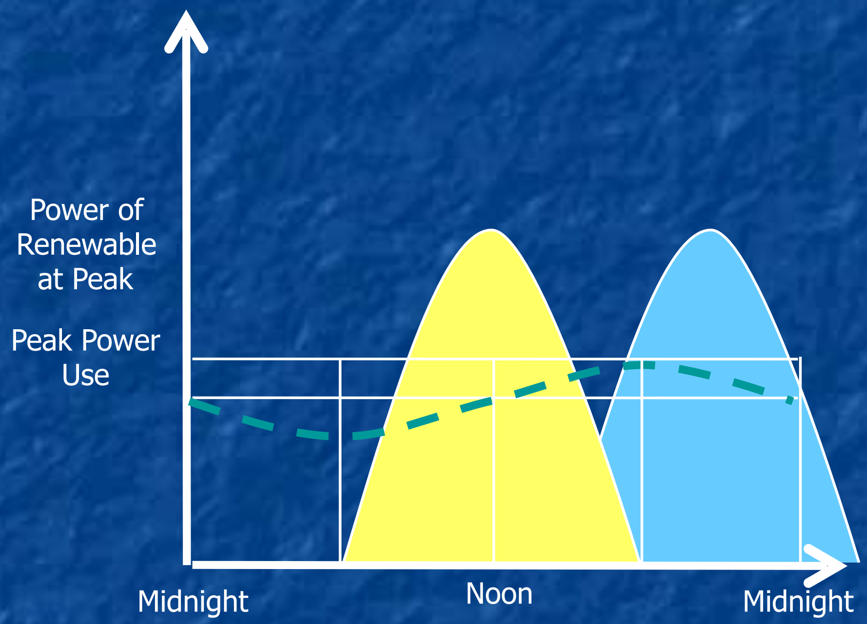
For preceding single sustainable, we'd have to store/save ~ **1/2 of power**

But above, for each sustainable, this might fall to ~ **1/3 of power**

A somewhat less limp solution: Use two renewables, from two time zones

For instance solar from here (in Virginia) + wind from California:

Peaks are then offset by ~ 6 hours (VA sun at noon EST, CA wind at ~ 6pm EST)



Exploiting time zone differences, we might only only have to store ~ **1/4 of power**

This is still well beyond our present day energy storage capability

But it might be done without **extraordinary** technology breakthroughs

However, we'd then confront: **long distance power transmission**

Which, frankly, we were going to have to confront **anyway**

From my note set **Power Plant Requirements: Land & Water** (pptx / pdf / key):

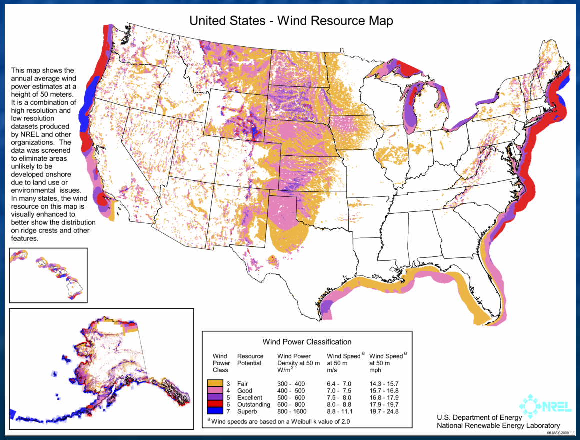
Renewable energy sources are SO DILUTE

That HUGE land areas are required to collect the power we now need/expect

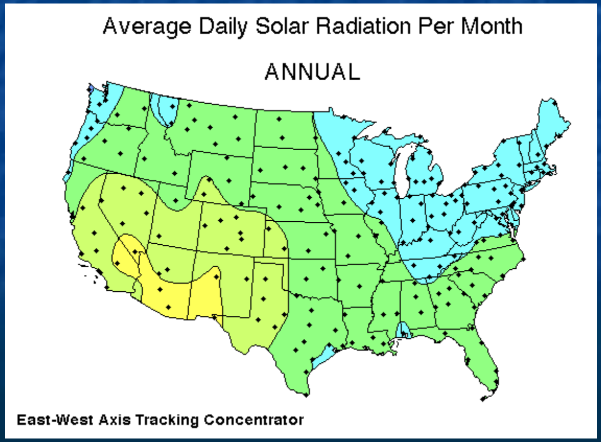
Providing a HUGE incentive to build renewable energy farms

WHERE renewable energy sources are at their **most intense**:

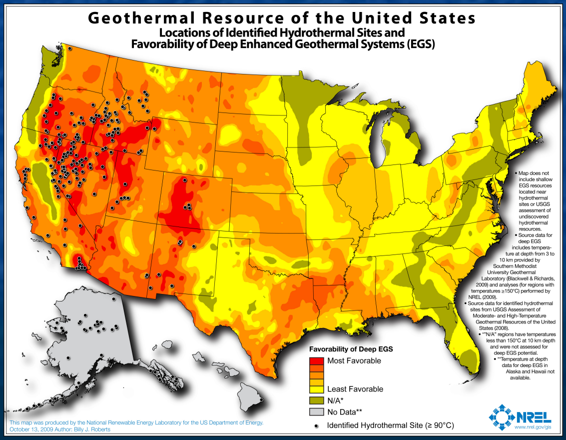
Wind map:



Solar map:



Geothermal map:



Losses and limits in long distance power transmission:

In my "Grid" note set I noted **three things limit such transmission**:

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

Due to flowing electron current knocking into atoms, heating them up

Compelling us to minimize electron flow = current

But then, to maintain power, the voltage must be proportionally increased

=> **High voltage / Low current AC or DC** for power transmission

In the future superconductivity might offer a solution to this limit:

In superconductors, resistive power loss disappears

And with it, our reason for avoiding high currents

=> **Low voltage / High current DC** for power transmission

But superconductivity **now** requires unacceptably low temperatures!

Next, as introduced in the "Generic Power Plant & Grid" lecture:

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

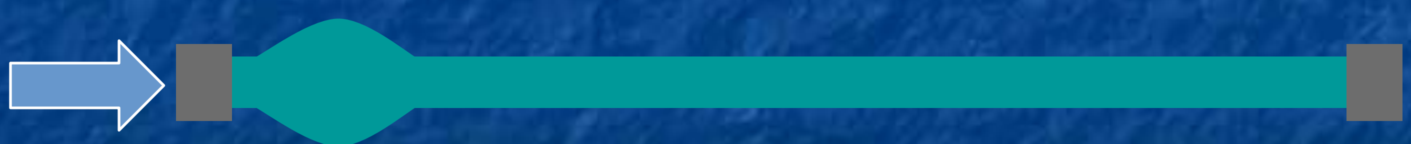
Due to **AC** current flow lagging behind the applied (pushing) voltage

=> **High voltage / Low current DC (only)** for power transmission

I explained this **consequence of magnetic field energy** via an analogy

A very stretchy rubber hose:

Turn on the faucet (electrical power), applying water pressure (voltage) to left end:

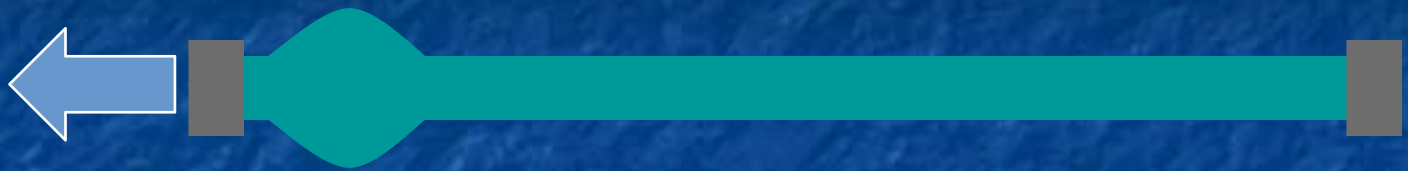


ONLY PART of the water (current) starts flowing **along** the pipe

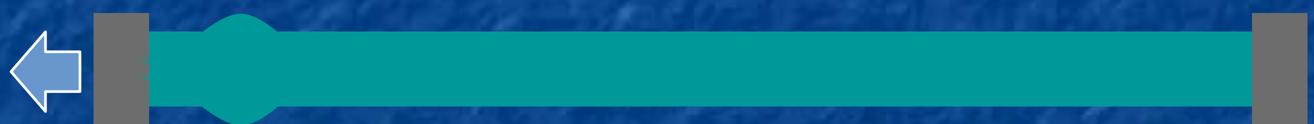
OTHER PART "induces" a growing bulge in the hose's wall!

If the faucet (power) is then quickly disconnected:

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

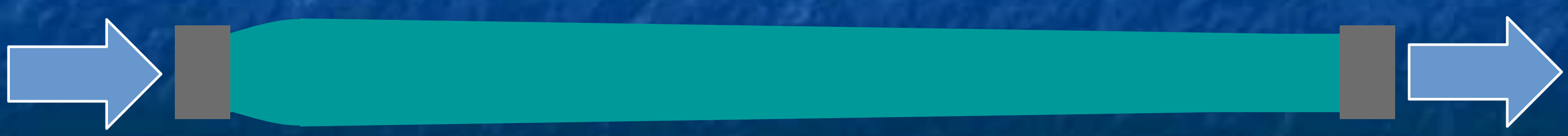


And this continues until the bulge fully relaxes:



Versus what would have happened if we'd just left faucet (power) on:

Bulge spreads out => Full length of hose expands slightly due to pressure:



Applied to a long power transmission line:

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

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

Because part of 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 go into pushing the electrons

And the growth of the current flow begins to catch up

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

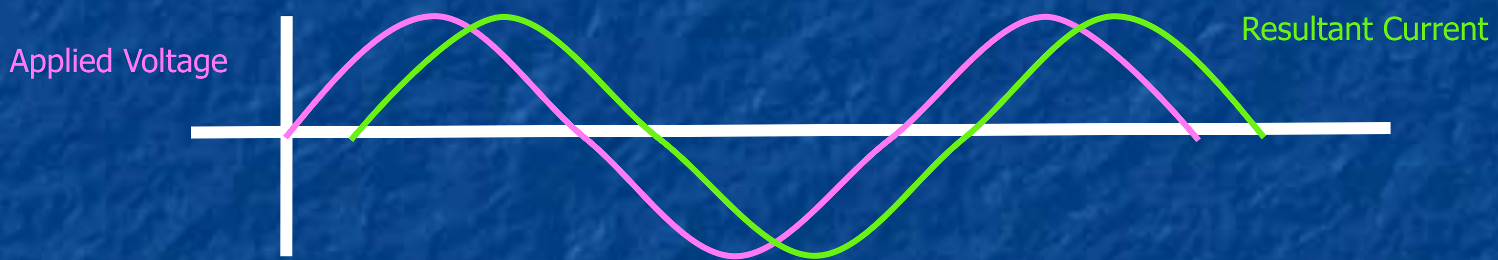
We expect the current flow to also fall to zero – but it doesn't!

Collapsing magnetic field continues to push electrons for awhile

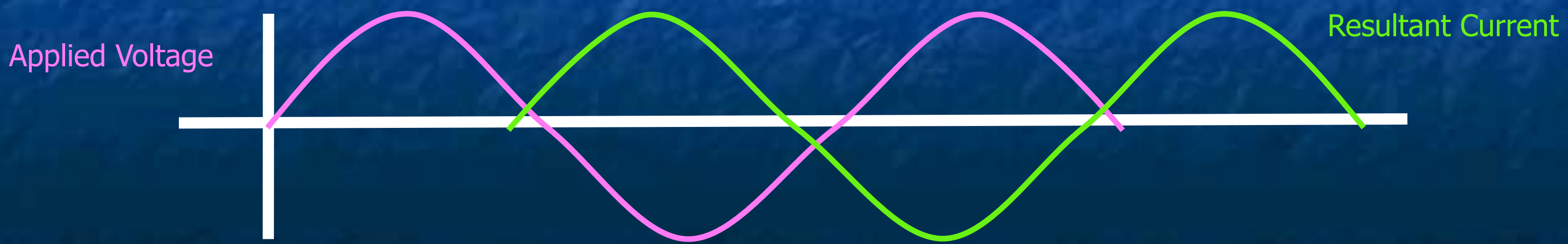
Result: Current flow lags behind the pushing voltage:

What we expected - not taking magnetic fields into account:

Out the end of a moderately long AC transmission line we instead get:



Out the end of a very long AC transmission line:



Longer line => Larger Lag => Less power out other end:

Short power line – Tiny current lag:

Long power line – Major current lag:

Voltage (V):

Current (I):

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

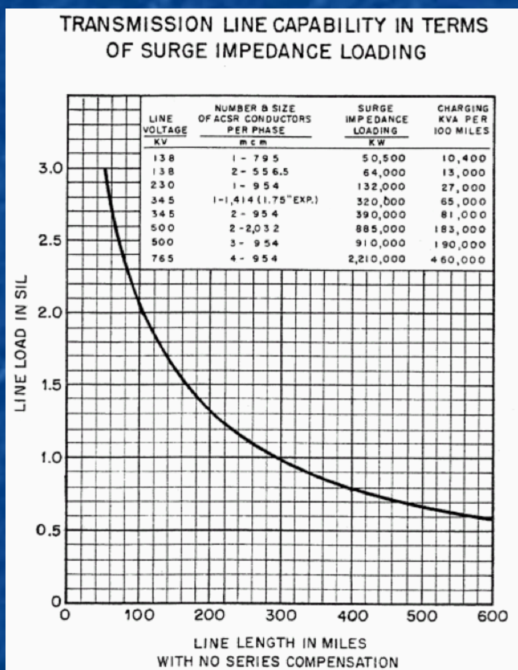
Far less power out (at right) when account for effect of magnetic energy storage!

Current lag plagues AC transmission lines - But not DC transmission lines:

Because lag is only important **just after** power is switched on, or off

Thus in continuously switching AC lines, current is **always** lagging behind

But in non-switching DC power lines, current quickly catches up



Leading to this American Electric Power Corp. plot:

Which says that power through AC power lines

plummets with in a few hundred miles!

All due to the AC voltage and AC current

getting more and more out of step

at the end of a long power line!

CONSEQUENCE? Today's largely **high voltage AC based transmission grid**

simply **cannot** effectively swap power across the entire country!

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&ved=0CEQQFjAF&url=https%3A%2F%2Fwww.pjm.com%2F~%2Fmedia%2Fcommittees-groups%2Fcommittees%2Fteac%2F20060711%2F20060710-aep-interstate-project-why-765kv-ac.ashx&ei=v1P8VK73CoKXgwT80oDIDQ&usg=AFQjCNFFTOyM9hVrGPhUJLEvCa8AEdnAEQ&sig2=vkGR8MKVGAwEWlb3m3g9uw&bvm=bv.87611401,d.eXY&cad=rja

Then there is the third limit, which also affects only AC:

3) Impossibility of synchronizing power from distant AC power plants

Derived from the fact that electrical power cannot flow faster than light speed

Which, traveling across US, takes a good fraction of a 60 Hz cycle time:

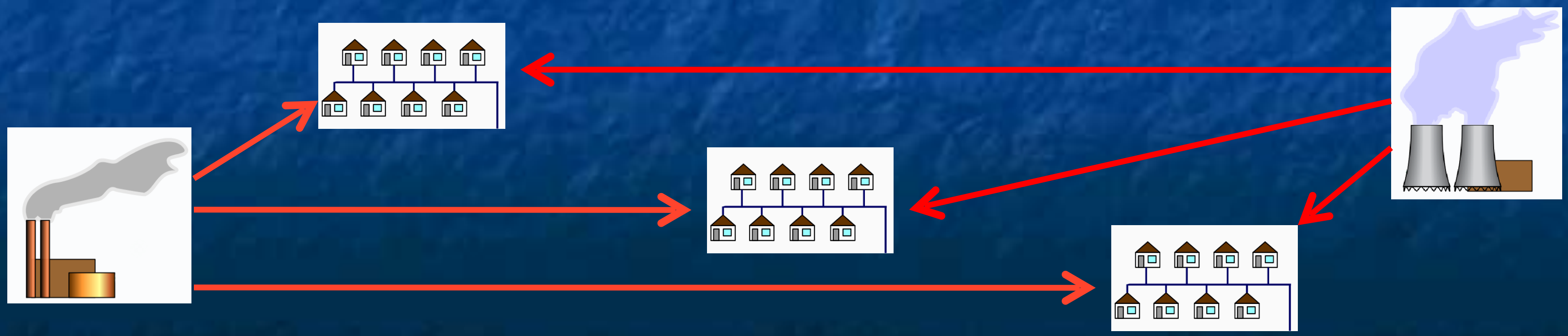
2500 mi / (186,000 mi/sec) ~ 1/100 sec vs. 1/60 sec

Meaning AC power from one distant AC power plant won't be precisely in phase

with the AC power coming from another distant AC power plant

We **could** tweak phase to realign for customers in one location

But not for multiple locations Or for power sent via multiple possible paths:

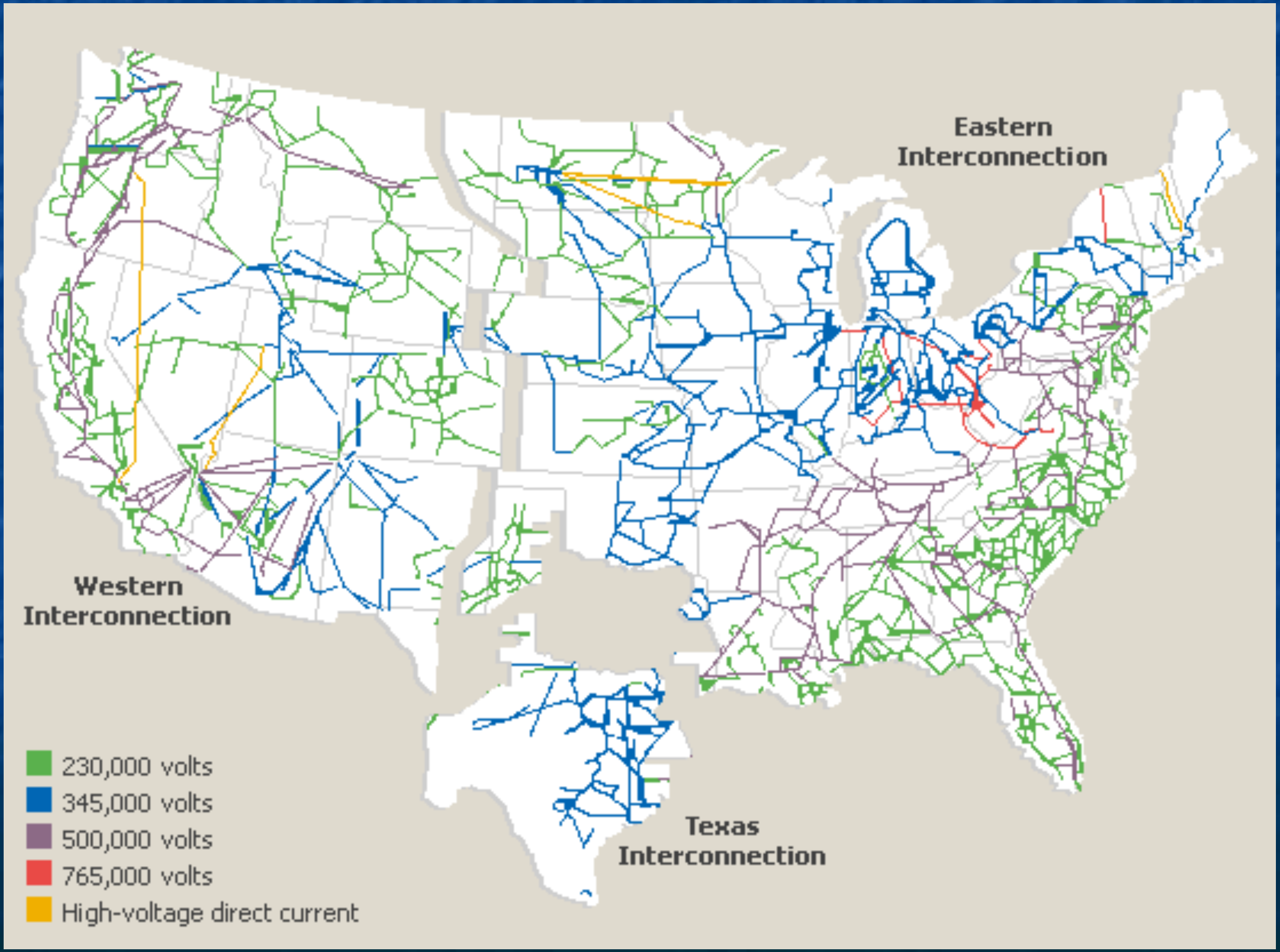


All driving us toward a grid with a strong high voltage DC backbone

But, instead, we now have only fragmented, weakly coupled, grid<u>s</u>

Making minimal use of HVDC transmission (the very few orange sections!)

http://www.geni.org/globalenergy/library/national_energy_grid/united-states-of-america/americannationalelectricitygrid.shtml

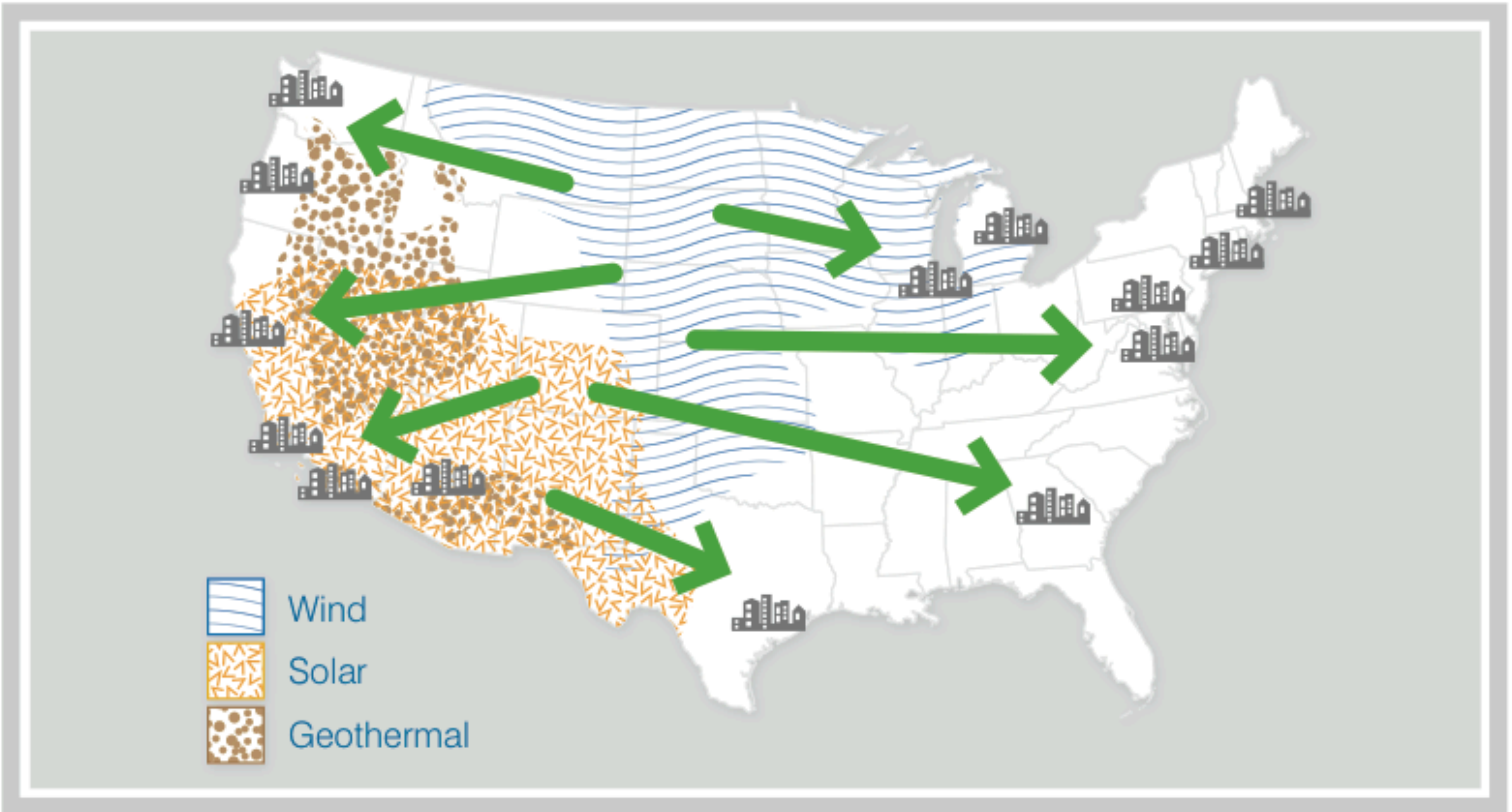


To share distributed renewable energy sources, we'd instead need:

A Green Power Superhighway, which has been proposed (surprise, surprise) by the

American Wind Energy Association & Solar Energy Industry Association [1]

FIGURE 1: **Nationwide Green Power Superhighways: A Conceptual Vision**



Source: AWEA and SEIA

http://www.awea.org/files/filedownloads/pdfs/greenpowersuperhighways.pdf

This is NREL's cheaper/short-term approximation to that proposal:

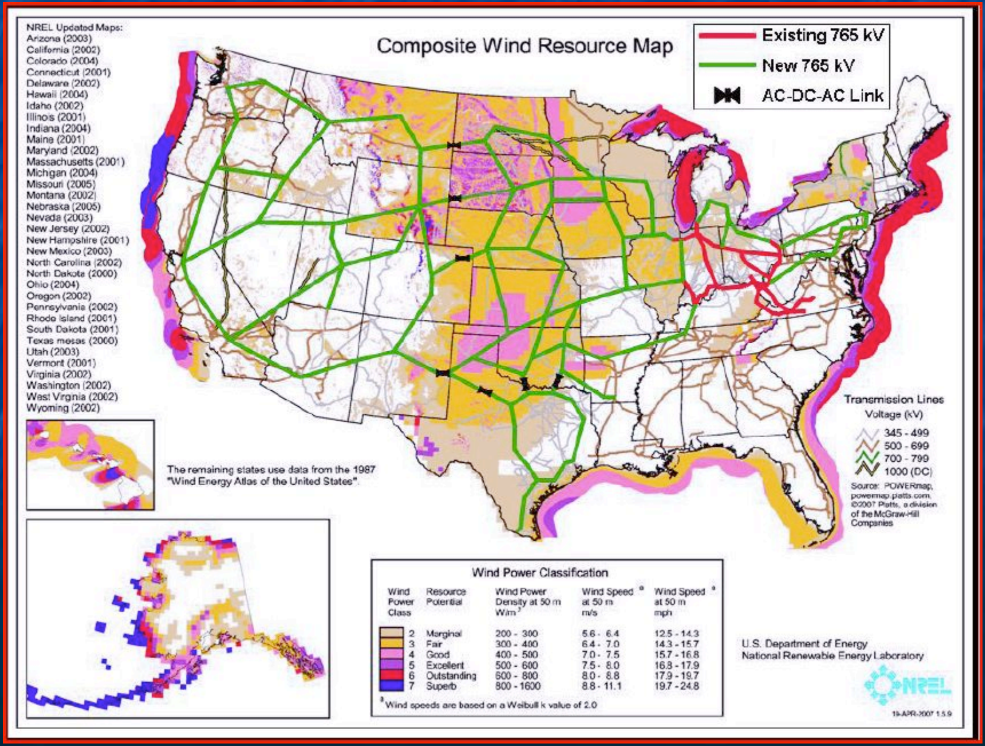
Nation-spanning links remain high voltage AC

But mid-route, **short high voltage DC links** would be inserted (black segments)

At these links, by going from AC to DC to new AC out:

- The voltage & current could be put back into step AND
- The new AC out of the link could be re-synchronized with the local power

Figure: http://https://http://www.geni.org/globalenergy/library/technical-articles/transmission/grid-integration-of-renewables/interstate-transmission-superhighways/index.shtml



This proposal really encapsulates the ***history*** *of US electrical power:*

1900: Dozens of **AC** power systems grow outward from major metropolitan areas

AC because transformers can match "best" voltage to each application

As **local grids** grow, they begin to move some power via **high voltage AC**

With that high voltage conversion **also** facilitated by transformers

Mid 1900's: **Regional grids** are finally almost all linked by **high voltage AC** lines

Creating **"The Grid"** which, we've learned, is really a bit of a myth

Late 1900's: Semiconductor-based integrated circuits finally came along

Facilitating "universal" conversion circuits => **HV DC** lines

Present Day: HV DC technology has improved

But it's cost still inhibits widespread adoption HV DC transmission lines

Preceding illustrates **technology** *issues of renewable / distributed grid*

But there are also major business, policy and even political issues:

Our current "big is generally better" power plants are, quite naturally,

almost always planned, financed, and built by very big power companies

Dominance of these companies led to them being granted **monopoly** status,

But only with monitoring by **Public Utility Commissions (PUC's)**

PUC's (supposedly) require these monopoly power companies to

Provide enough affordable power, now and in the future:

Minutes from now - When we demand that our power be restored!

Decades from now – Requiring whole new generations of power plants

But a Renewable / Distributed Grid will be hugely more complicated:

Instead of a single, huge, solely responsible (and accountable) provider,

Any small business or home owner can buy a small solar array

And set themselves up as micro-power company

But what if China then used their domination of solar cell production to up prices?

Or a new federal administration decided to drop a solar tax subsidy?

Micro-power CEO's (= you and me) would stop buying arrays

U.S. power supply would crash, power prices would skyrocket . . .

So I'm betting we'll want the freedom of having **personal** micro-power systems

While still expecting a **large power company** to retain core responsibility

Including, holding power company responsible for "base load"

Because renewables alone, even with plausible levels of energy storage,

Are just not capable of providing enough power, all through the day

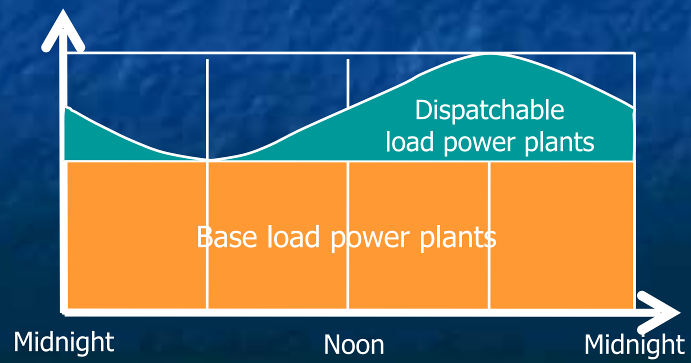
So we still need a 24/7 "base load" supply of power

Of a magnitude demanding huge hydrocarbon power plants

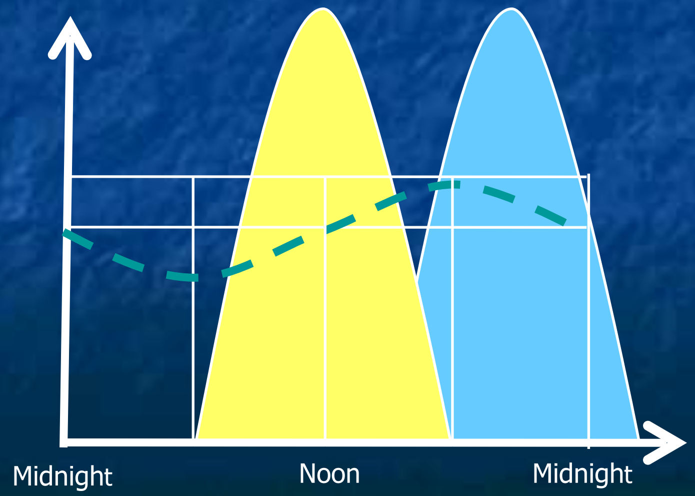
Or, for greener power, hydroelectric or nuclear power plants

Either of which will require retention of large (if not monopoly) public utilities:

In other words, this works:



But this (alone) doesn't:



AND we'll have to figure payments to micro-power producers (you & me):

1) First alternative: **NET METERING**

= You pay for the NET power you draw from grid

= (Power used in your home) – (Power produced in your home)

When sending power to grid, you'd expect payment at power's current cost / worth

Midday payment should be ~ average value

But evening payments should be higher!

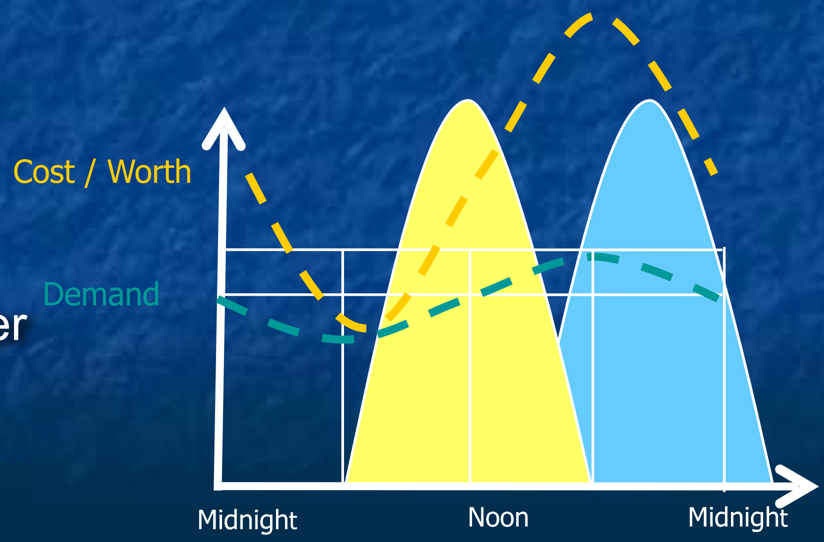
But "fairness" gets very controversial

And in some states you get paid only

power's **minimum** daily cost /worth,

no matter **when** you supply that power

(e.g., as now occurs in Virginia)



Alternative micro-power payment scheme = Feed In Tariffs:

Net Metering (above) was blind to HOW the homeowner generates power

But what if a state WANTS citizens to invest in, say, **rooftop solar cell panels**?

Perhaps, to protect scarce, local, now-undeveloped land

from conversion into wind-farms or solar farms

Some states do this via **FEED IN TARIFFS (FITs)**

Which are payment rates that depend on HOW you produced your power

E.G., rate for power from rooftop solar can be pegged HIGHER

But you then need TWO POWER METERS on your home:

1st Meter to measure power you draw from grid => Payment **from you**

2nd Meter to measure power you send to grid => FIT payment(s) **to you**

Kept separate because payment rates (¢ents/kW-h) will differ!

And to make things even MORE complicated:

During emergencies, household meters will have to SHUT OFF your power to grid

So that power company repair crews

will not be electrocuted:

Photo: https://www.pacificpower.net/ed/po/or/wwdtrp.html

Balance of power from power company vs. micro-power providers will also be critical

Because BIG power plants can take a decade or more to build

And must then operate for ~ 30-40 years to recover their costs

So the micro-power share (from us) must somehow be stabilized

Giving power companies time to build or gracefully retire power plants

BOTTOM LINE:

To power companies, Renewable/Distributed Grid = Potential Chaos

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