GEOS 24705 / ENST 24705

Lecture 11: mechanical -> mechanical (wind and water, the modern version)

Can’t wring more power out of existing consumption of coal

Electricity production is growing… but steam turbines no longer growing in efficiency

Note:
* exponential growth in several stages

* topping-out of steam P and T ca. 1960

* Still well below Carnot limit

  - intrinsic to Rankine cycle?
  - unnecessary waste heat in condensation stage?
  - turbine design?

From Vaclav Smil, “Energy at the Crossroads”

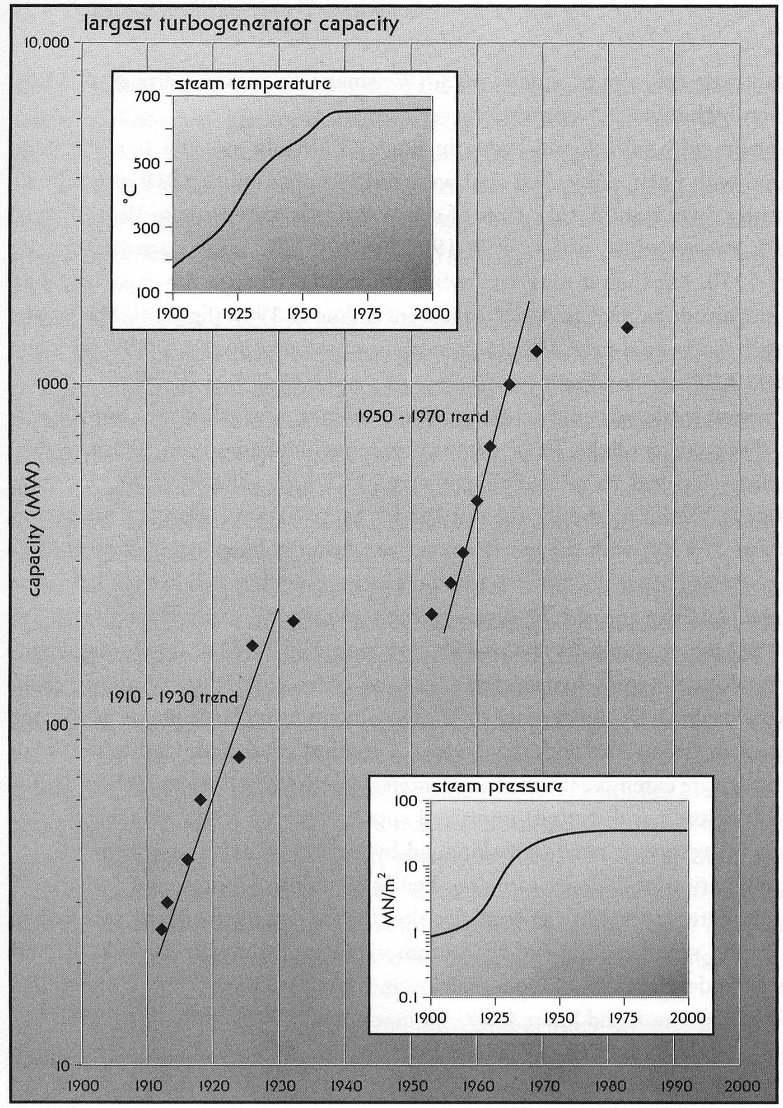


Figure 1.9
Record ratings of the U.S. turbogenerators during the twentieth century. Growth of the highest capacities was interrupted by the economic crisis, WWII, and the postwar recovery; afterward the precrisis growth rate resumed for another two decades. Both the top operating temperatures and the highest pressure used in modern turbogenerators have not increased since the 1960s. Based on data in FPC (1964), various issues of *Power Engineering*, and a figure in Smil (1999a).

… but steam turbines no longer increasing in efficiency

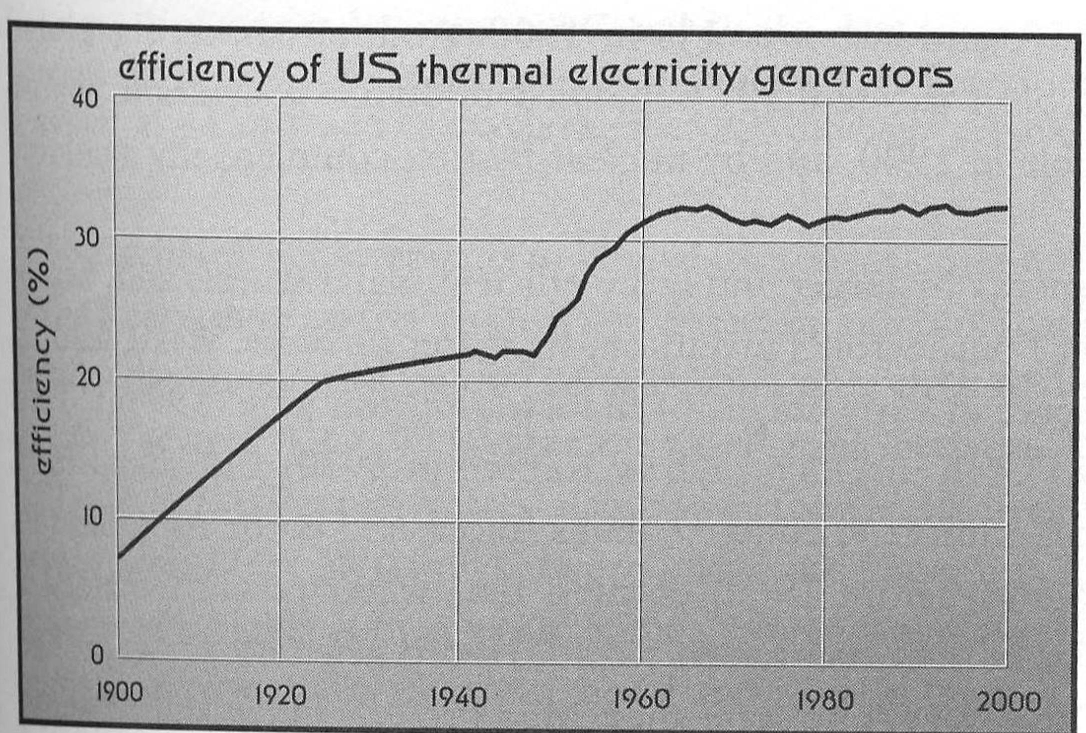
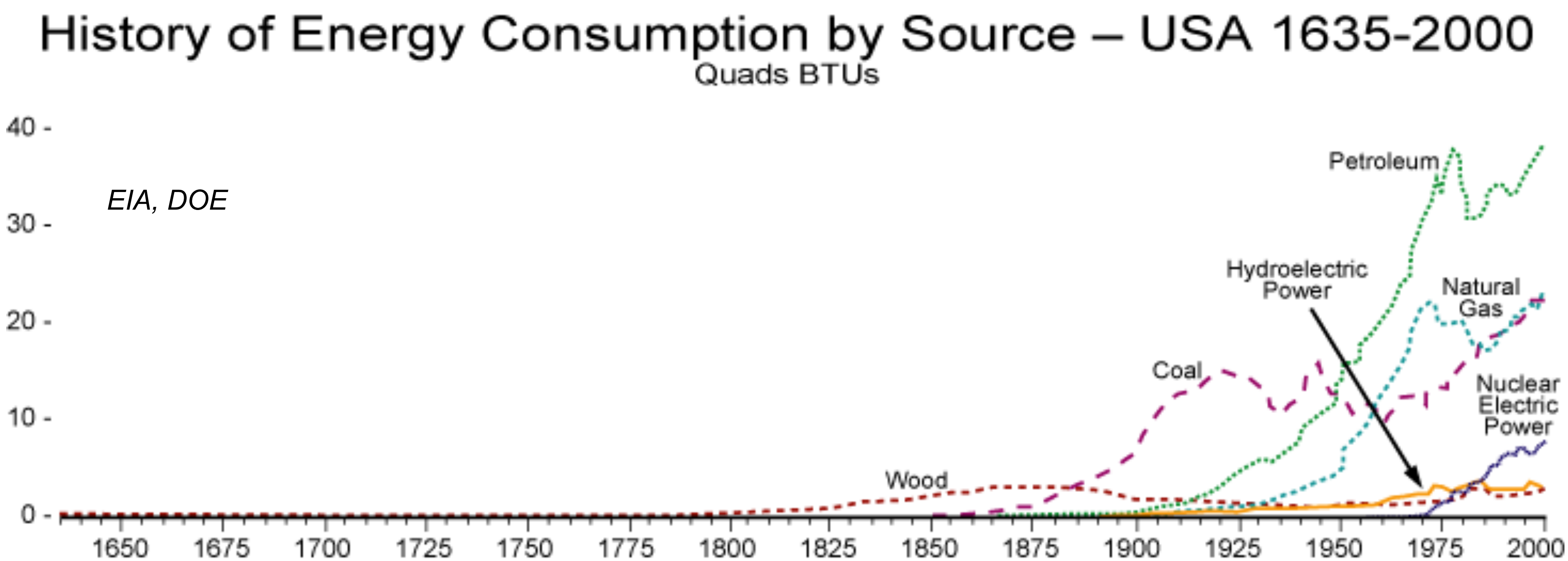


Figure 1.17
By 1960 the average efficiency of the U.S. thermal generation of electricity surpassed 30% and while the best power plants now operate with efficiencies just above 40% the nationwide mean has stagnated for 49 years, clearly an unacceptable waste of resources. Plotted from data in USBC (1975) and EIA (2001a).

From Vaclav Smil, "Energy at the Crossroads"

Hydro close to maxed out

Largest renewable but not much room for growth, efficiencies optimized by mid-1800s



Use:

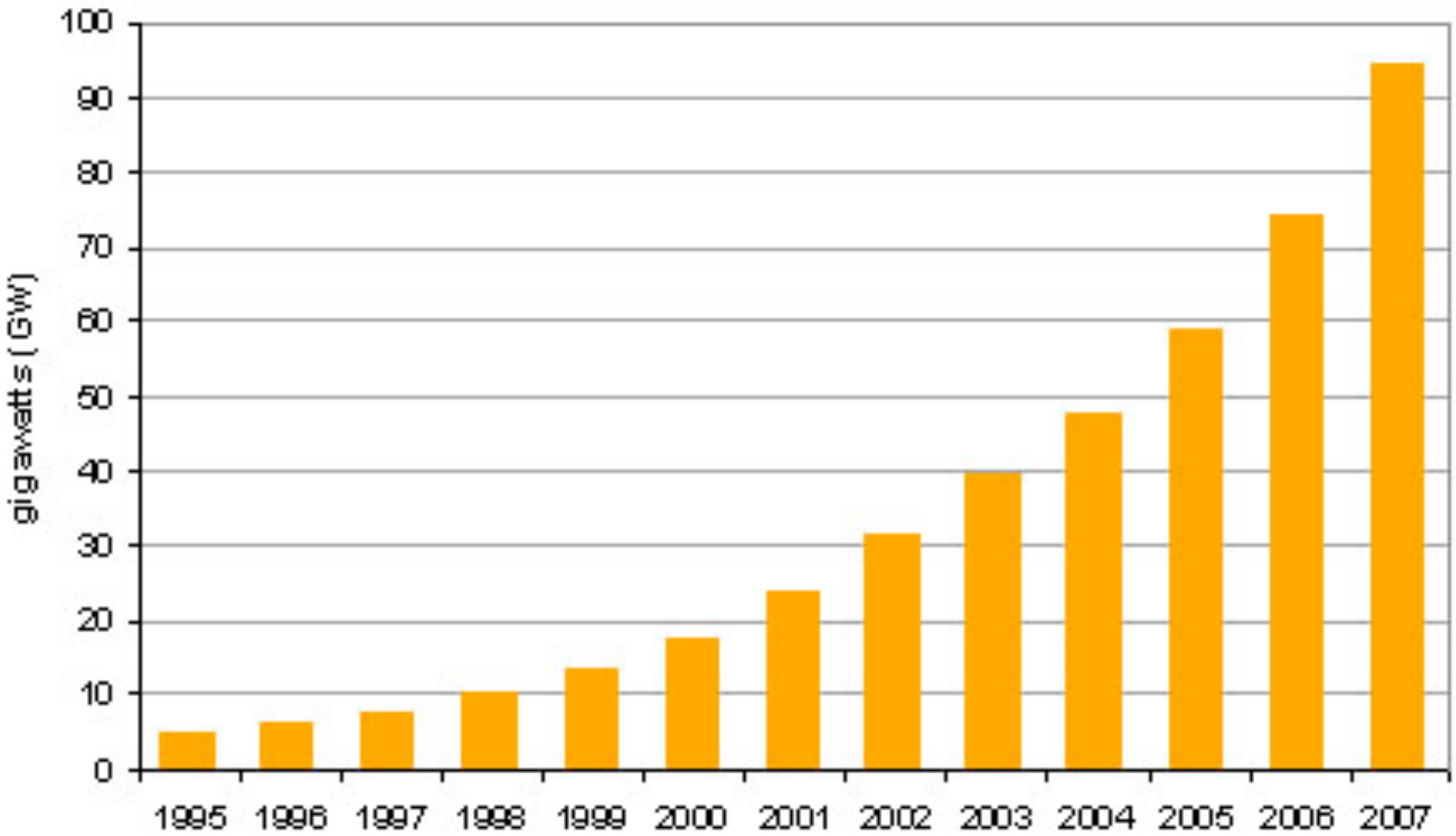
Right now hydro is ~3 QuadBTU/~100 = 3% of U.S. energy use
So 300 W / person (given that average power use is 10,000 W
Each U.S. person has > 5 acres ~ 20,000 m2, lets say ~30,000 m2
Hydro use is therefore right now ~ 1 W/1000 m2 = **.01 W/m2**

Total possible in extreme unrealistic conditions (trap every raindrop in U.S.):

1 m rain/yr = 1 m3/m2 rain
@ 1g/cm3 = 1M g/m3 = 1000 kg/m3 -> rainfall is 1000 kg/m2*yr
Potential energy of 1 kg water behind 100 m dam is mgh = 1000 J
Power = 10^6 J/m2 in 1 yr or 10^6/(365.*24*3600.) W/m2 = (1/3)*$10^6/10^7$ **= .03 W/m2**

Wind increasing sharply

Far less important at present, but more potential growth



World Resources Institute,
from IEA data

Pros and cons of hydro

Pros

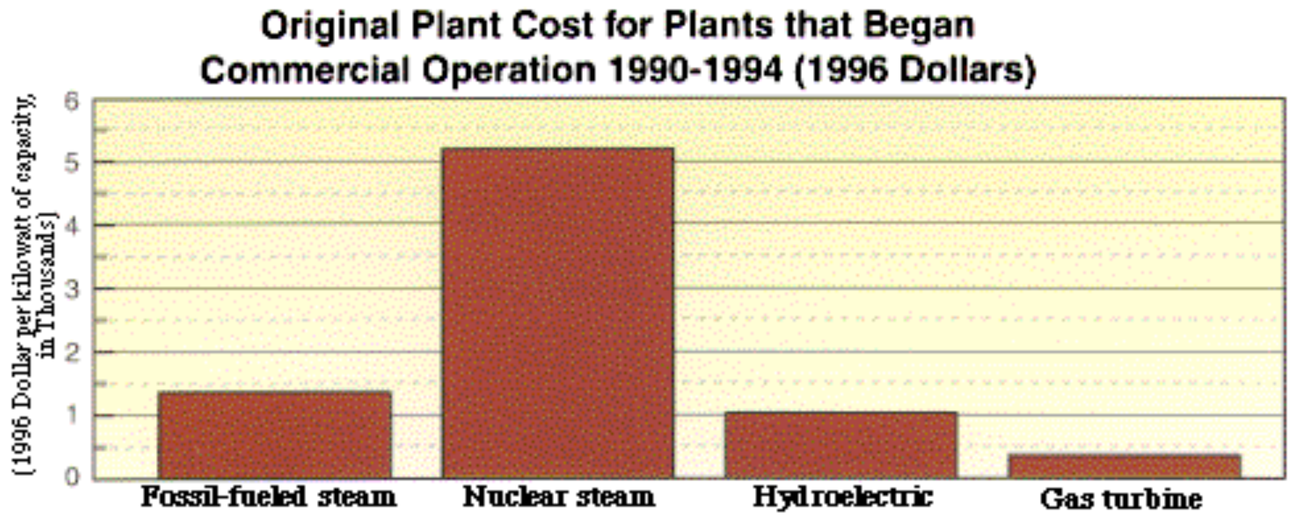
- CO_2–free (nearly)
- Low maintenance over long life
- .. and zero fuel cost..
- … means in long term is extremely cheap and simple energy source
- Infinitely schedulable – fast turn–on
- Reliable (compared to e.g. wind, solar)

Cons

- Environmentally destructive
- Socially destructive
- Capacity not ultimately great enough to meet all world’s energy needs

Hydro has high capital cost (> $1000/kW) but long life and low operating costs

Can go even higher, to $3000/kW for dam and hydro system. So hydro install cost is $1-3/W, more than most fossil plants.



But given hydro stations' long life and low operating cost, hydro has lowest average cost of electricity of all generation options.

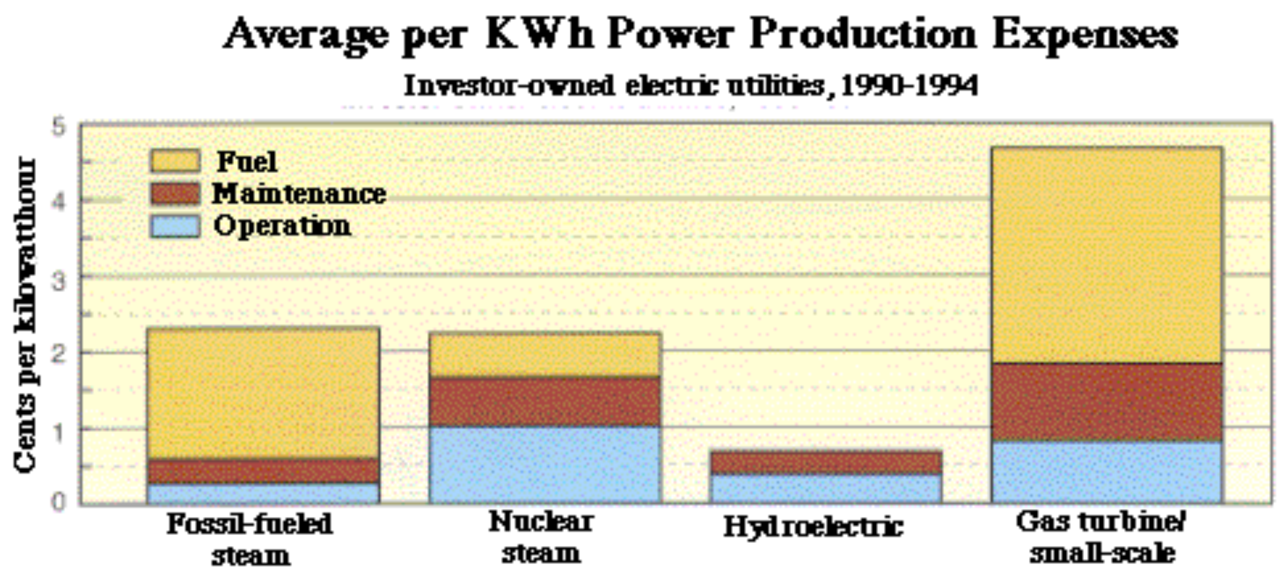
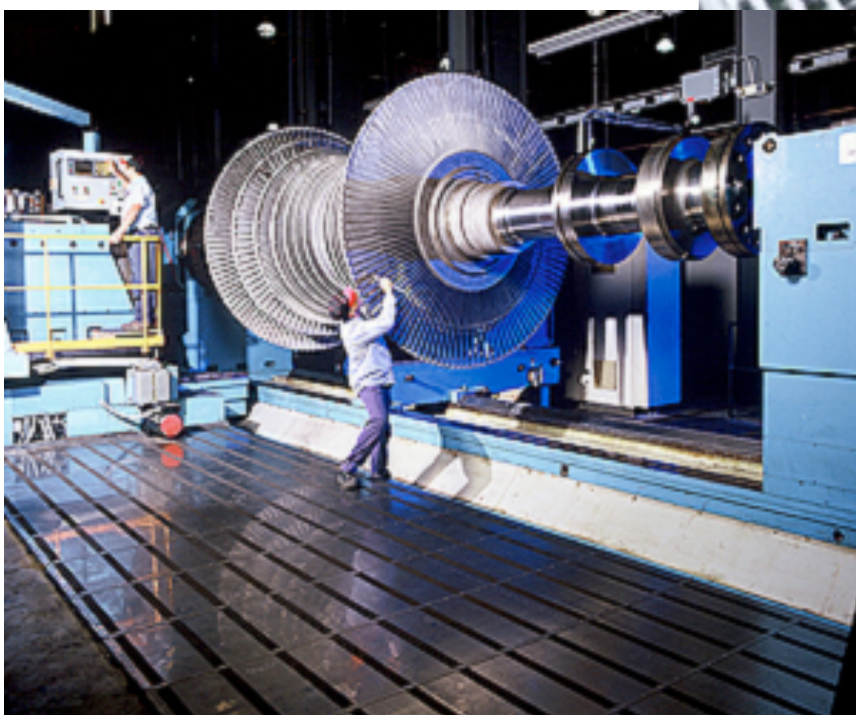
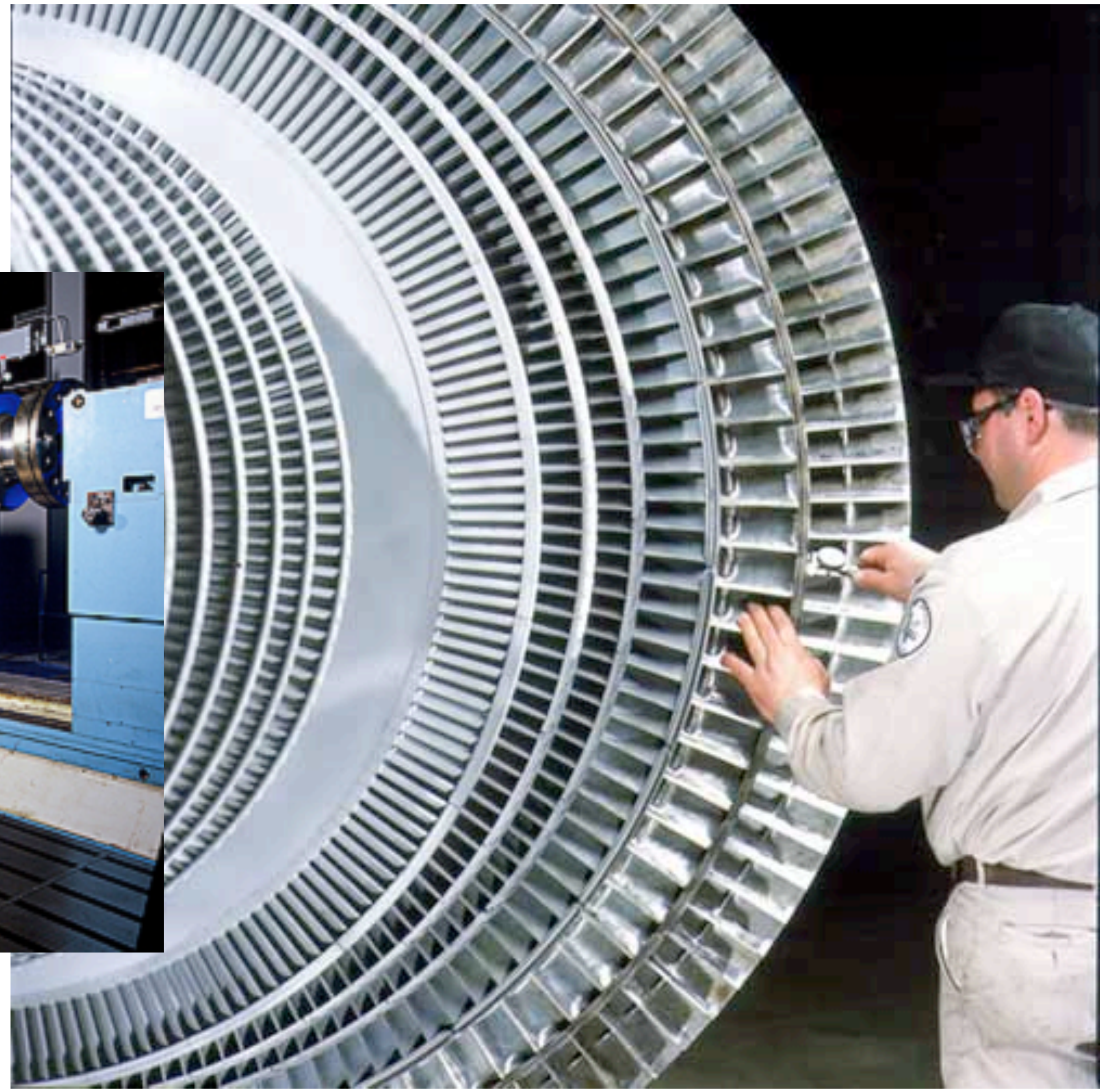


Figure: source unknown

No hydro or wind turbine looks like a gas turbine
Why not?

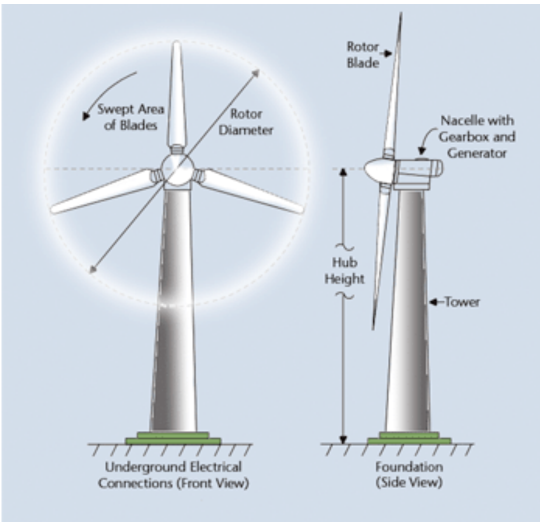




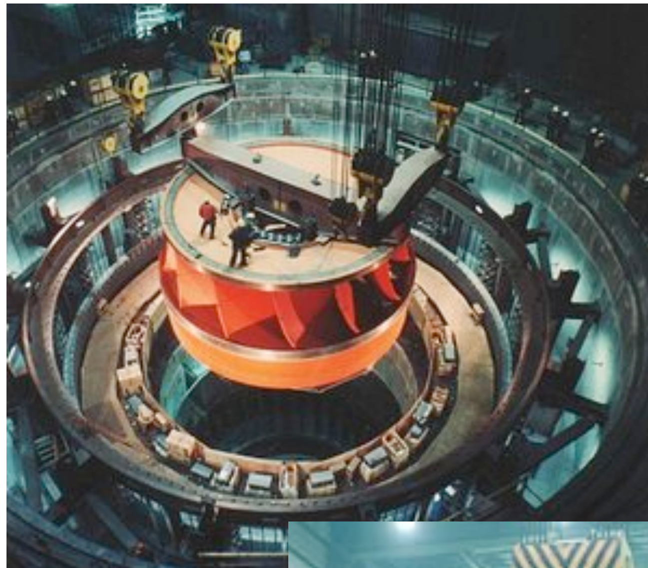
Physics of hydro and wind turbines

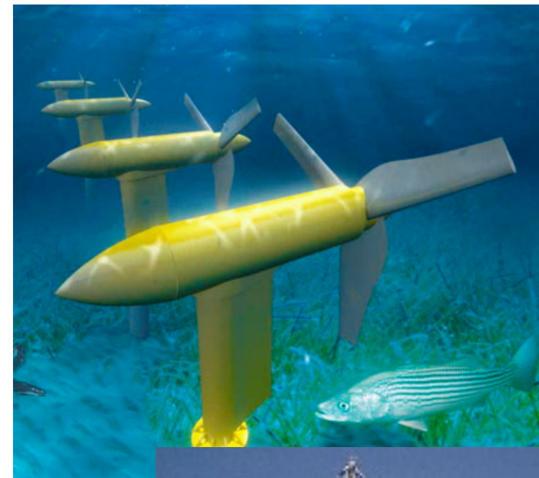
All designed to use flowing fluid to rotate something

Yet enormous diversity of designs – what governs the choice?



Drawing of the rotor and blades of a wind turbine, courtesy of ESN





Criteria driving turbine design

- Velocity (v)
- And/or initial pressure of fluid (P)
- (and whether you can control fluid pressure)
- And/or density of fluid (ρ)

v, P, and ρ all contribute to energy density of fluid

Turbines can extract energy via:

- Changing speed of fluid – *"impulse"*
- Changing pressure of fluid – *"reaction"*

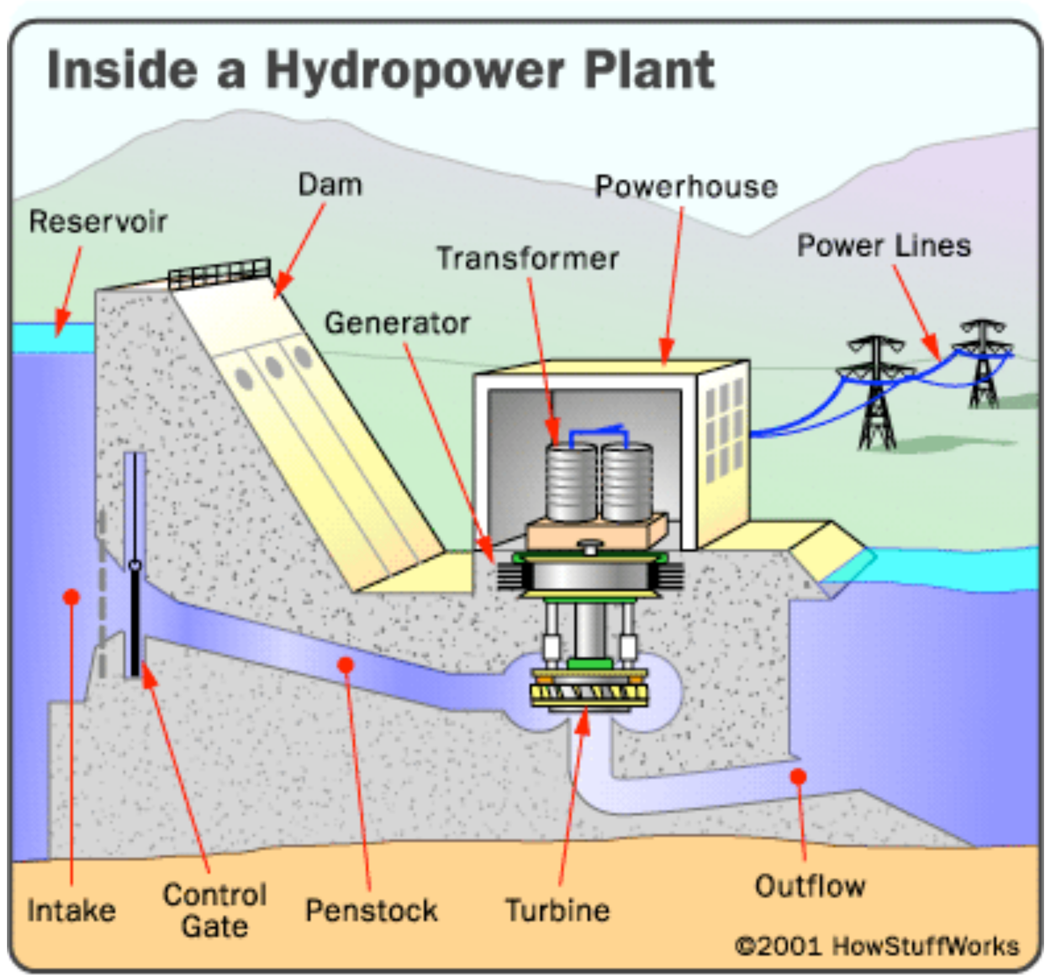
… and in fact you can trade off between these when you manipulate your flow

… or can design a turbine that combines strategies

Why are dams so important in hydro power?

Because raising head allows harnessing energy that is otherwise lost during flow of river

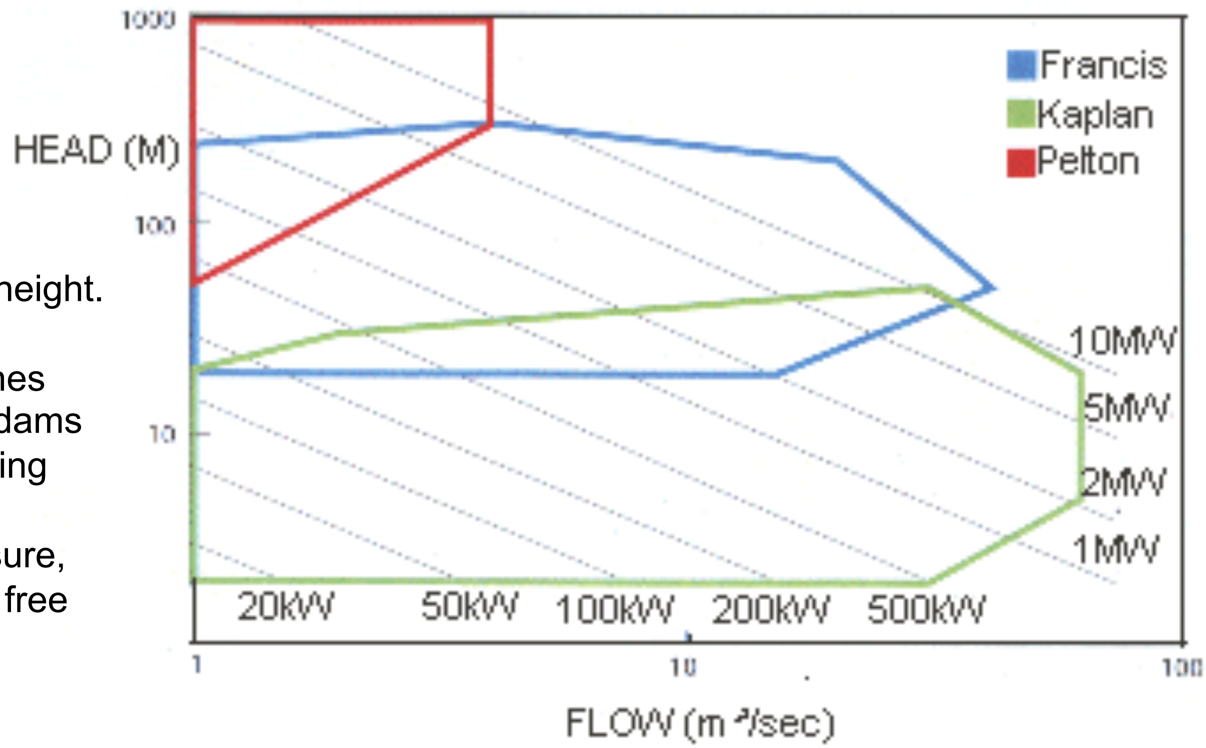
Entire Amazon in run-of-river mode would produce 10x less power than single dam on Columbia River



Hydro turbine design set by flow rate and pressure

“head” = dam height.

All these turbines are used with dams or other confining structures to increase pressure, as opposed to free “run-of-river”



Note that you can get the same amount of power from high head and low flow (a small amount of high-energy fluid), or from low head and high flow (a large amount of low-energy fluid).

Three main types of hydro turbines

1. Pelton
2. Francis
3. Kaplan
4. *plus* various free-stream turbines (very low head)

Pelton, Kaplan, and Francis turbines

HydroTurbineAnimation

1. Pelton wheel: *impulse turbine* (high head: up to 1000 m)

The direct descendent of the water wheel…

Turbine turns in air, impelled by water from nozzle – same principle as steam or gas turbine, except the nozzle sprays a liquid (water) instead of a gas (steam or air)

Direct heritage from water-wheel, but uses nozzle rather than just falling water

Can be quite large, up to 300 MW (vs. 1 GW for Francis)

1. Pelton wheel: impulse turbine (high head: up to 1000 m... ...or low flow in “run-of-river” mode)

Note that even in micro-hydro use (defined as < 1 KW), control fluid pressure and velocity with inlet nozzles.

Although used as a “run-of-river” turbine, don’t just put it in the water and let it spin. Spinning in air is much more efficient, so needs sealed box.

Nozzles and a box are fairly cheap and simple.

For electric generation, micro-hydro can’t generate 60 Hz AC but is OK for DC generation.

Can’t generate enough power to match American lifestyle but can bring some power to areas where there is none.

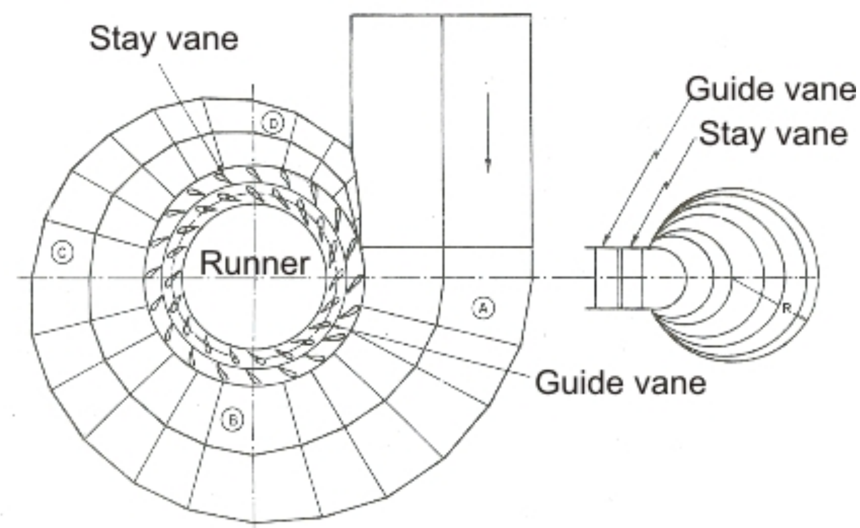
2. Francis turbine: *reaction turbine*
(medium head: 10 - 500 m)

Design – 1848, James Francis, for Lowell Mills. 90% efficiency

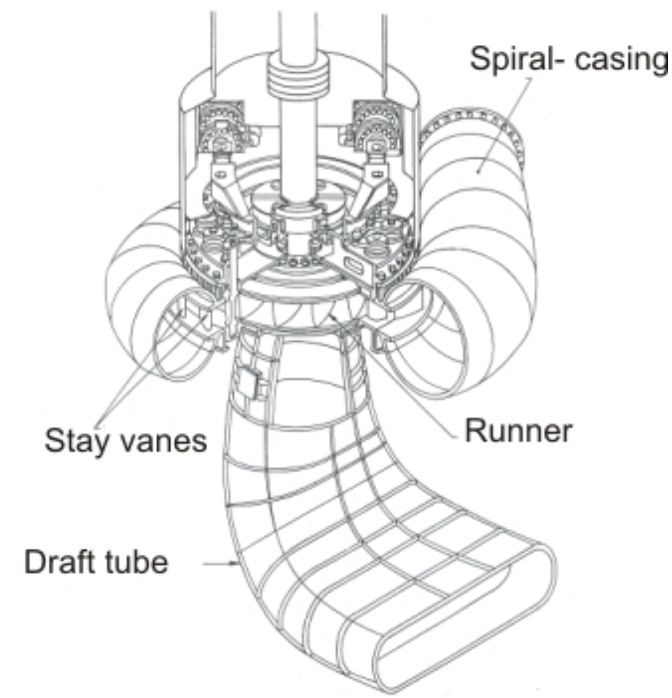
First hydroelectric plant in U.S. was a waterwheel in New York, 1869.. But 25 years later the Niagara Falls plant (where Tesla established primacy of AC power) used Francis turbines

Francis turbines are now the workhorse of modern hydro – overwhelming majority

Vertical axis, like oldest of waterwheels
Radial (inwards) flow into runner



(a) Plan view (b) Elevation

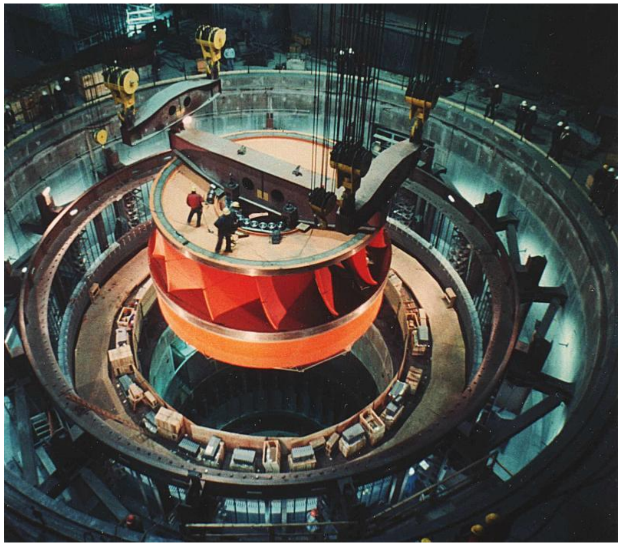


Energy extracted via drop in pressure. Velocity ~ constant in turbine til draft tube

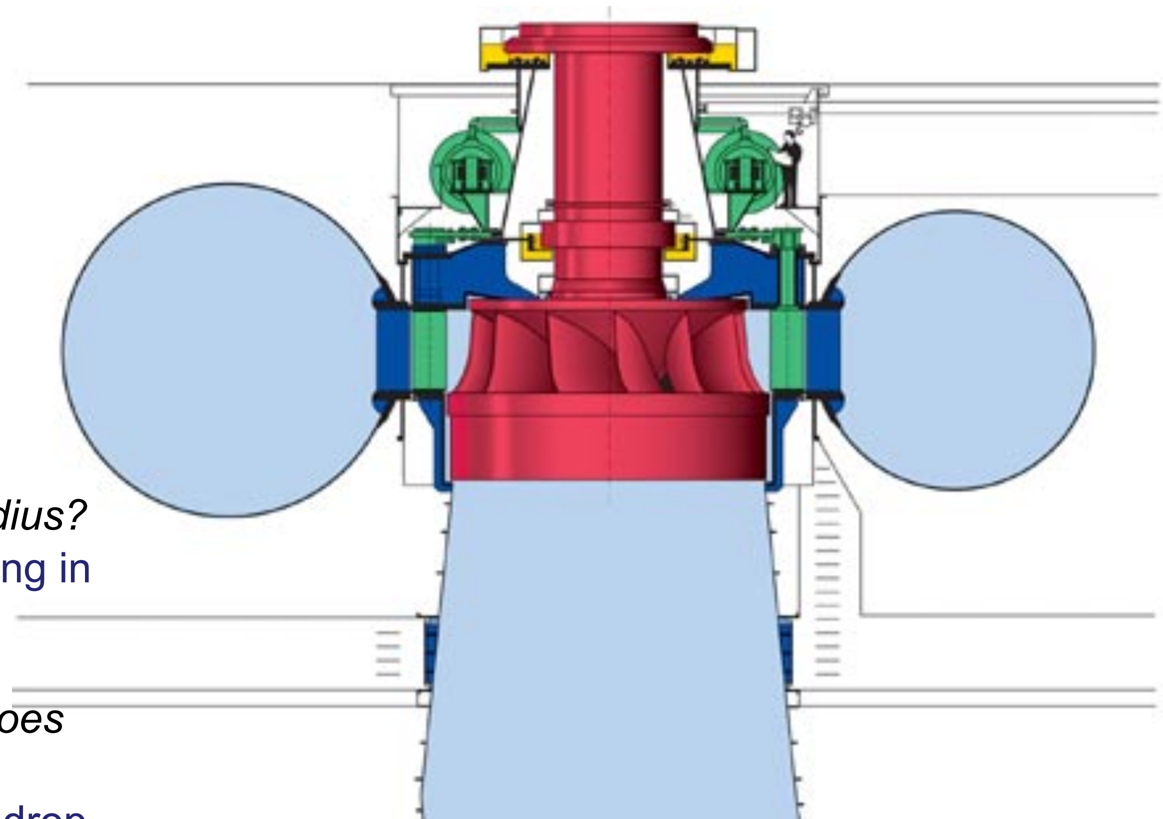
Hydro is topped out in efficiency but getting bigger for cost…
Efficiency of scale lowers cost

Francis turbine runner from Three Gorges Dam project, China (900 MW)

Runner is only small part of entire turbine assembly



Francis turbine runner from Grand Coulee Dam (L)



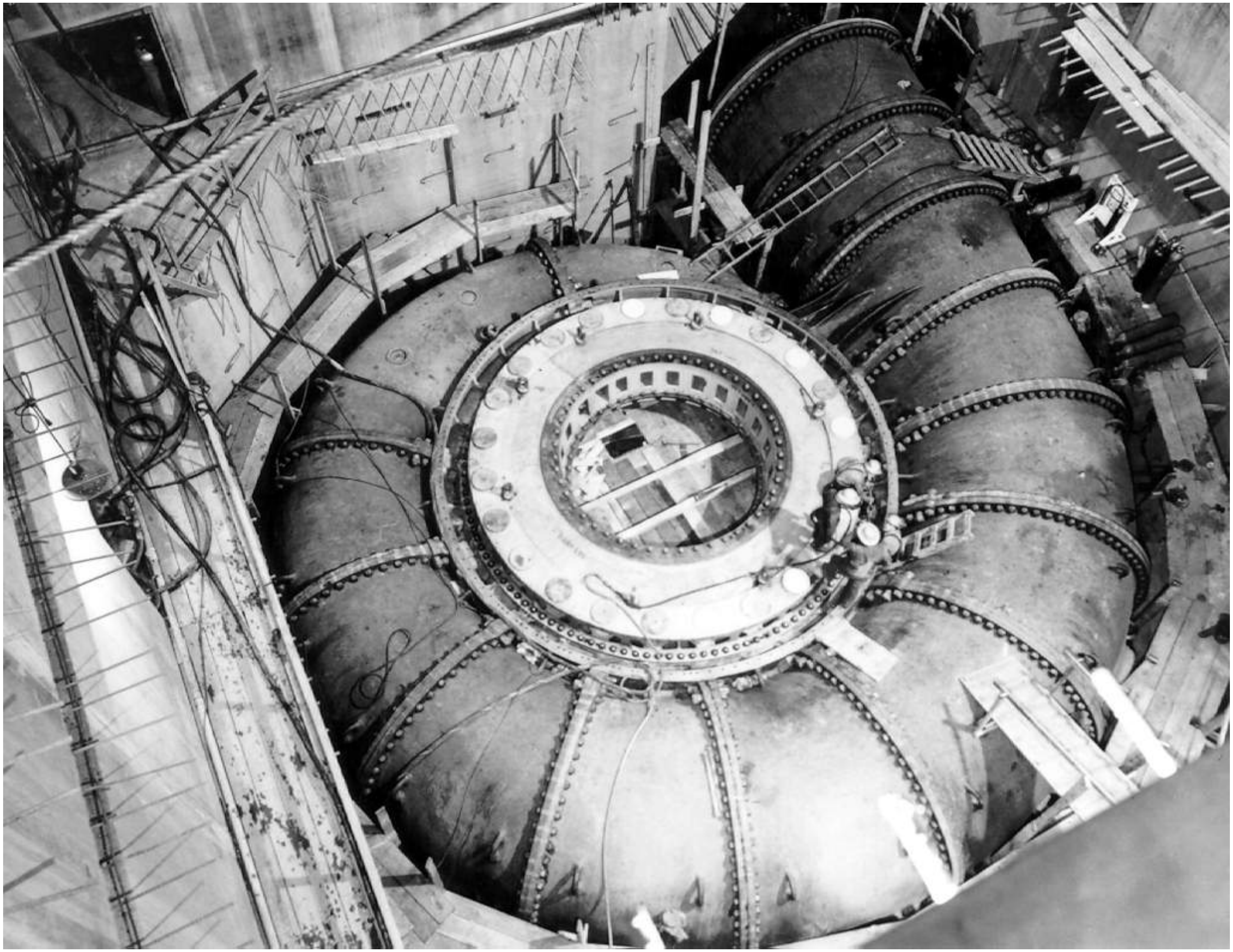
cutaway from Voith-Siemens

Design questions:

Why does input spiral decrease in radius?
Because flow is radial – water is flowing in to center and actually lost

What is function of draft tube? Why does that fan outwards?
To produce slow-down of motion and drop in pressure (it's an anti-nozzle), which extracts last possible energy from fluid.

Runner is only small part of entire turbine assembly



Francis turbine intake spiral from Grand Coulee Dam

Hydro power plant operation

Three Gorges Dam Animation

Three Gorges:

Currently largest hydropower system in operation: 2 dams, > 21 GW total capacity now, to exceed 25 GW

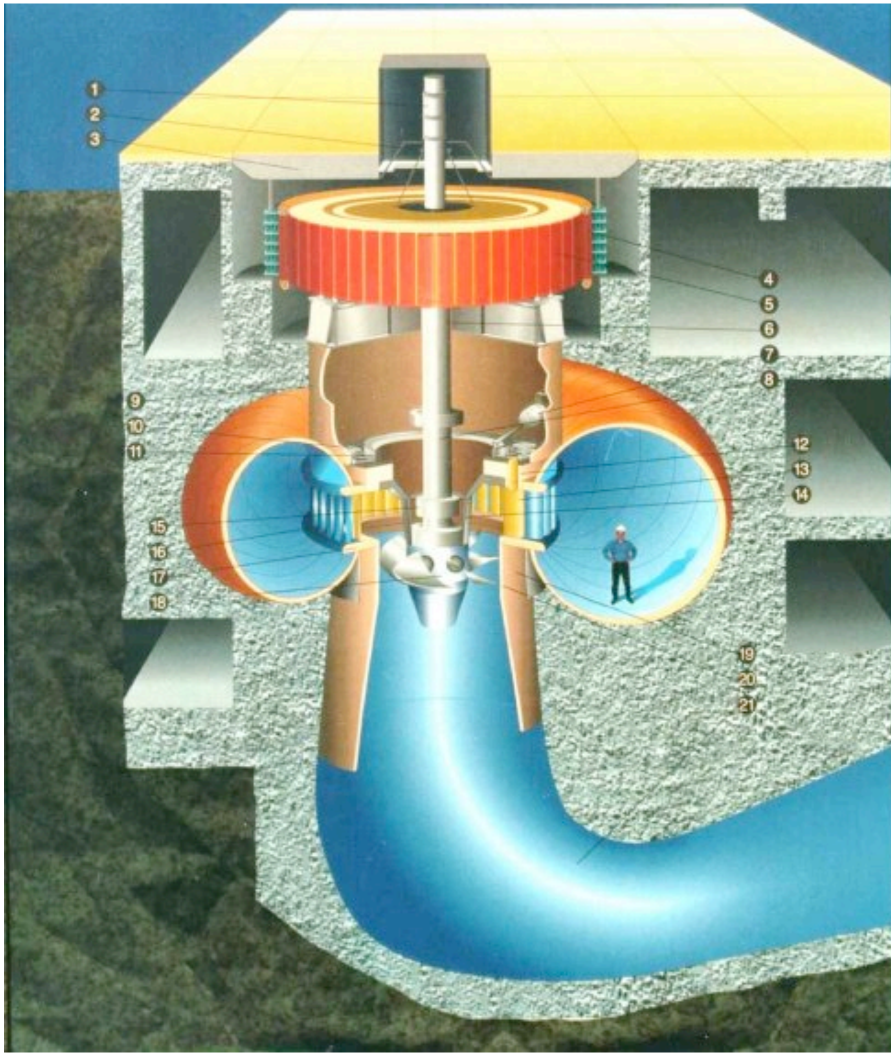
China is already largest hydropower producer in the world

Most of new mega-size hydropower projects under construction are in China

Why? Lots of people, low (current) per capita energy use, limited energy sources – already buy coal from Australia.

3. Kaplan turbine: *reaction turbine* (low head: 2-30 m)

Vertical axis, inward radial flow like Francis … but starts to look like a propeller



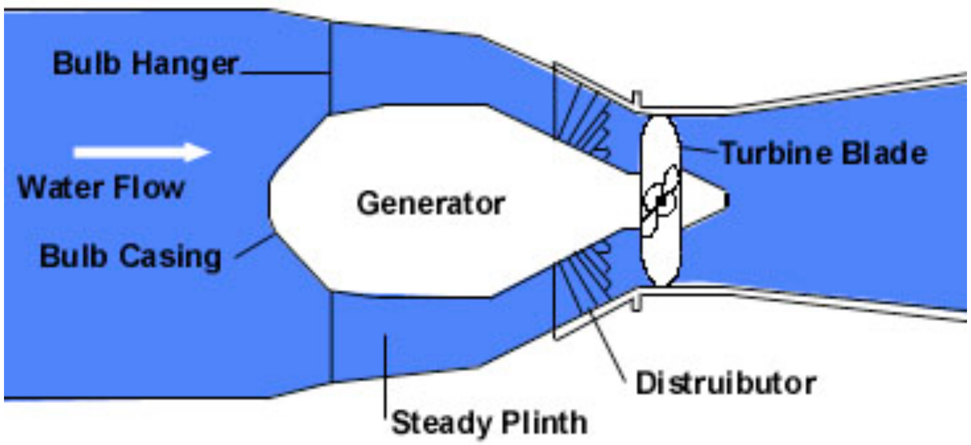
Granite Canal Hydroelectric Project, Newfoundland

Running wheel of a Kaplan turbine made by Tampella, year 1950, photograph V.O. Kanninen

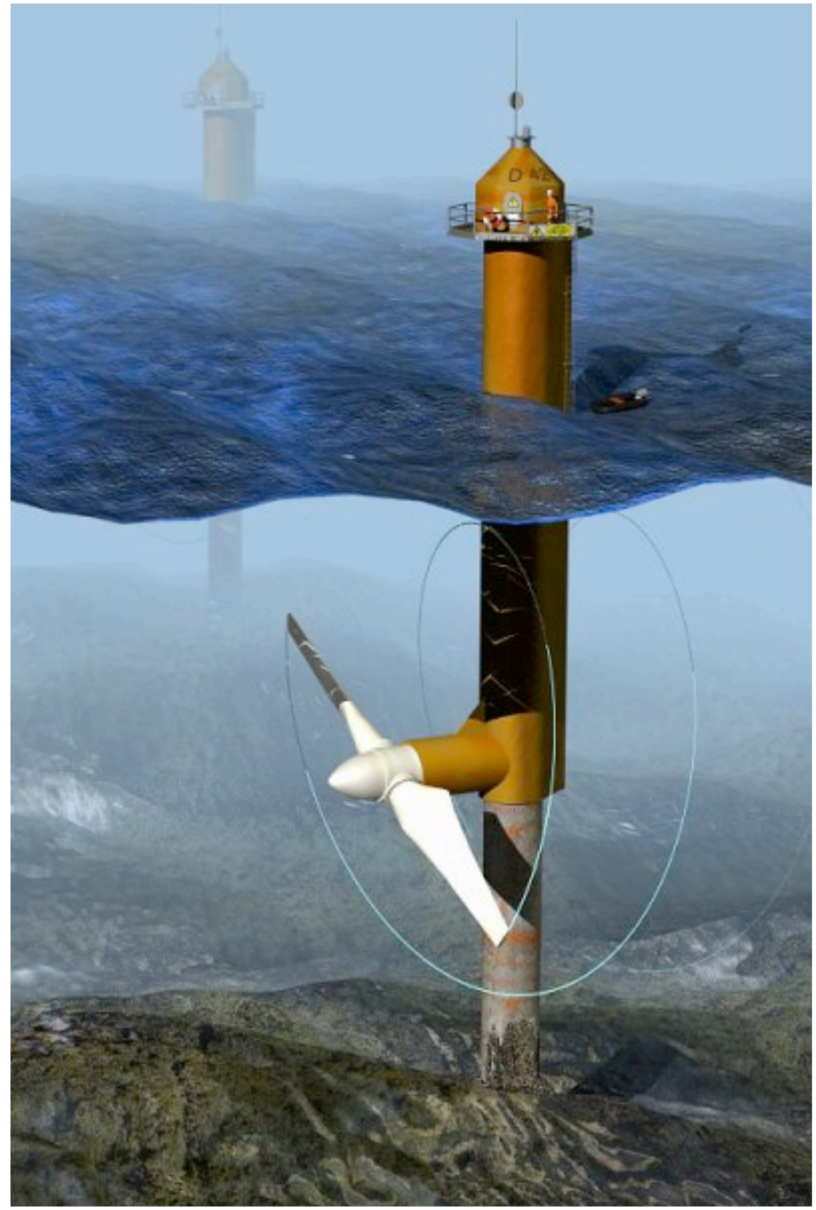
4. Free-stream: *impulse turbines*

If have a casing, can get a bit of p control, but pressure changes are small.

Fully impulse turbines start to look a lot like wind turbines…*since they operate similarly, extracting kinetic energy only from a low-energy-density fluid*



Bulb turbine, La Rance tidal plant, St. Malo, France (Research Institute for Sustainable Energy, figure originally from Boyle, 1996). Here there may be some pressure control via the casing, making this a mixed impulse-reaction turbine (both p and v drop across the turbine).



Artist's rendition of marine current turbine for extracting energy from tidal flows (Tidal Stream Inc.). No casing, so no control of pressure at all. Note that is turning in water, unlike Pelton wheel – simpler but less efficient.

4. Free-stream turbine: *impulse only*

If no casing, no pressure-sealed box, then really start to look a lot like wind turbines…
but seem 10 x less powerful

"EnCurrent" in-stream run-of-river hydro turbine with permanent-magnet DC generator, 5 kW, optional grid tie AC converter, for sale by ABS Alaskan, $28,000

($6/W purchase cost before installation – not a cheap option)

Vertical axis wind turbine with permanent-magnet DC generator: 500 W, 24 Volt VAWT Darrieus variant known as a Giromill. 4 foot diameter, 20.8A, 24 V. Start up wind speed is 3 m/s (around 7mph), and the rated wind speed is 13 m/s. $1500

($3/W rated before installation, and that is for rated wind only – actual capacity will be much much less, pushing to $10-100/W… see wind lecture to follow)

Questions:

Why does a similar wind turbine seem lower-power than a similar hydro turbine?

Why are most powerful wind turbines in general so much smaller than biggest hydro? (7 MW vs. > 1 GW)

Why are wind turbines so large in size?