Water is guided to the turbine via a “penstock” that controls flow and pressure.

Image: Xeneca Corp.
3 main dam hydro turbine designs
choice governed by flow rate and pressure

Pelton (1870s)
High head, low flow
*Impulse turbine used with dam or container*

Francis (1848)
Medium head, all but highest flows
*Pure reaction turbine*

Kaplan (1922)
Low head, all flows
*Pure reaction turbine*

Images: L. Voith Siemens
M. Copyright unknown
R. Photo V.O. Kanninen
1. Francis turbine: *reaction turbine*
   (medium head: 10 - 500 m)

Hydro getting bigger...

Efficiency already near max – but larger scale lowers cost

*Francis turbine runner from Three Gorges Dam project, China (700 MW)*
1. Francis turbine: *reaction turbine*
*(medium head: 10 - 500 m)*

Design – 1848, James Francis, for Lowell Mills (direct-drive), had 90% efficiency already in 1848. 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. Now Francis is the dominant form for dam hydro.

Runner is only small part of turbine assembly
Inlet spiral is even larger

Francis turbine intake spiral from Grand Coulee Dam
Runner is only small part of turbine assembly

Francis turbine runner from Grand Coulee Dam (L) Cutaway from Voith-Siemens (R)

Design questions:

What is the input spiral for? Why does it decrease in radius?
The spiral directs water **radially** to the runner. Because water flows in to center and is lost, the diameter has to narrow to keep pressure and velocity constant.

What is the function of the draft tube? Why does it fan outwards?
To produce a slow-down of motion and drop in pressure. (It’s an “anti-nozzle”)
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2. Kaplan turbine: reaction turbine (low head: 2-30 m)

Now starts to look like a propeller...

Running wheel of a Kaplan turbine made by Tampella, year 1950, photograph V.O. Kanninen
2. Kaplan turbine: *reaction turbine* (low head: 2-30 m)

*Can be used with vertical axis and inlet spiral like a Francis turbine*
*Or with horizontal axis, with pressure drop provided by enclosure and “bulb”*
3. Pelton wheel: *impulse turbine* (high head: up to 1000 m)

A water wheel with a nozzle

Turbine turns in air, impelled by water from nozzle – pure impulse turbine, just force of water striking “scoops” on wheel

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

**Bernoulli’s equation: turn pressure gradient energy into kinetic energy.**

Can be quite large, up to 300 MW (vs. 1 GW for Francis)
3. Pelton wheel: *impulse turbine*
also used for low-head micro-hydro

Pelton wheel is simple and therefore cheap, good for micro-hydro (＜1 kW).

Even in micro-hydro use, control fluid pressure and velocity with inlet nozzles rather than putting wheel in river and letting it spin.

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.
4. Free-stream turbine:

DEFINITIONS
“Run-of-river” = no dam
“free stream” = not even a penstock, so no pressure drop at all

No pressure gradient = ?
= impulse turbine only

These start to look even more like propellers... a lot like wind turbines...
Wind
GEOS 24705/ ENST 24705
Energy in a flow

Energy/mass = \( \frac{1}{2} v^2 + gh + \frac{p}{\rho} \)

- kinetic
- gravitational
- pressure gradient

Power = energy/mass * mass/time

Flow q = mass/time
= volume*density/time

Volume = area * length
Velocity = length/time

Power = energy/mass * density * area * velocity

\[ P = \varepsilon \cdot \rho \cdot A \cdot v \]
Energy in a flow: dam hydro

Energy/mass = \( \frac{1}{2} v^2 \) + \( gh \) + \( \frac{p}{\rho} \)

- **kinetic**
- **gravitational**
- **pressure gradient**

Power = energy/mass * mass/time

Flow \( q = \) mass/time = volume * density/time

Volume = area * length
Velocity = length/time

Power = energy/mass * density * area * velocity

\[ P = \varepsilon \cdot \rho \cdot A \cdot v \]

\( \varepsilon = gh \)

\[ P = gh \rho A v \]
Energy in a flow: kinetic term only

Energy/mass = \( \frac{1}{2} v^2 \) + g h + \( \frac{p}{\rho} \)

- kinetic
- gravitational
- pressure gradient

Power = energy/mass * mass/time

Flow q = mass/time
= volume * density/time

Volume = area * length
Velocity = length/time

Power = energy/mass * density * area * velocity
\[ P = \varepsilon \cdot \rho \cdot A \cdot v \]
\[ \varepsilon = \frac{1}{2} v^2 \]
\[ P = \frac{1}{2} \rho A v^3 \]
Early windmills run mechanical pumps only

Icon of the American west is a fully automatic pump for lifting water for cattle, invented by Halladay in 1854. “Drag” type windmill, horizontal axis. (Note timing -> OK land rush, 1889)

Images: IronMan Windmill Co.
Early wind turbines are “drag” turbines

James Blyth, Scotland, 1887
vertical axis “drag” type

Charles Brush, Cleveland, 1888
17 m diameter
12 kW, used for electricity gen.

Blades “pushed” around by impact of air striking them

Images: Wikimedia
Modern wind turbines are “lift” turbines

Blades “pulled” around by low-pressure as air flows over airfoil shape

Lift blades can generate more force than drag turbines – extract more of wind’s energy
Windpower increasing rapidly

Wind increasing by more than 15%/yr. (doubling in 4 years)

World energy use increasing at 2%/yr (doubling in 35 years)

Still only 1% of global energy use, though
Wind turbine size also increasing
What drives that change?

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Wind turbine size also increasing
What drives that change?
Wind turbine size also increasing

What drives that change?

- Longer blades – more power per turbine built
- Higher wind speeds
- Power increase by a factor of 60
Micro-wind is not the norm

Most turbines now installed are 1 MW or more. Record is 7.5 MW (Clipper Britannia).

R. Enercon E-126, 126 m. rotor diameter (413 feet), 6 MW rated (likely 7+ in practice).
L. Clipper Liberty, 2.5 MW

Images: source, copyright unknown
Wind speed increases with altitude
Means turbines must be high to get good wind

Power carried by wind is a function of cube of wind speed
\[ P = \frac{1}{2} \rho A v^3 \]

Max area \( A \propto \) square of hub height (higher hub allows longer arms). 
Microwind (short towers) is inherently inefficient.
Why only three blades?

Blades do not touch all air molecules that pass through turbine x-section.

Answer: blades can affect flow of all air that passes through x-section without touching every molecule.
Can’t get all the energy out of a flow

To get all the kinetic energy you’d need to stop the flow

Wind turbine disturbs the flow, makes a “cone” of high -> low velocity

Rotor velocity is average of upstream and downstream

\[ v_{\text{rotor}} = \frac{1}{2} (v_1 + v_2) \]

Max power extracted when slow flow down by 66%:

\[ \frac{v_2}{v_1} = \frac{1}{3} \]

Max energy extracted is then 59% of total

\[ v_{\text{rotor}} = \frac{2}{3} v_1 \]

And solve for energy extraction

Images: (T) FTexploring.com (B) Wikimedia