ECE 530: Contemporary Energy Applications

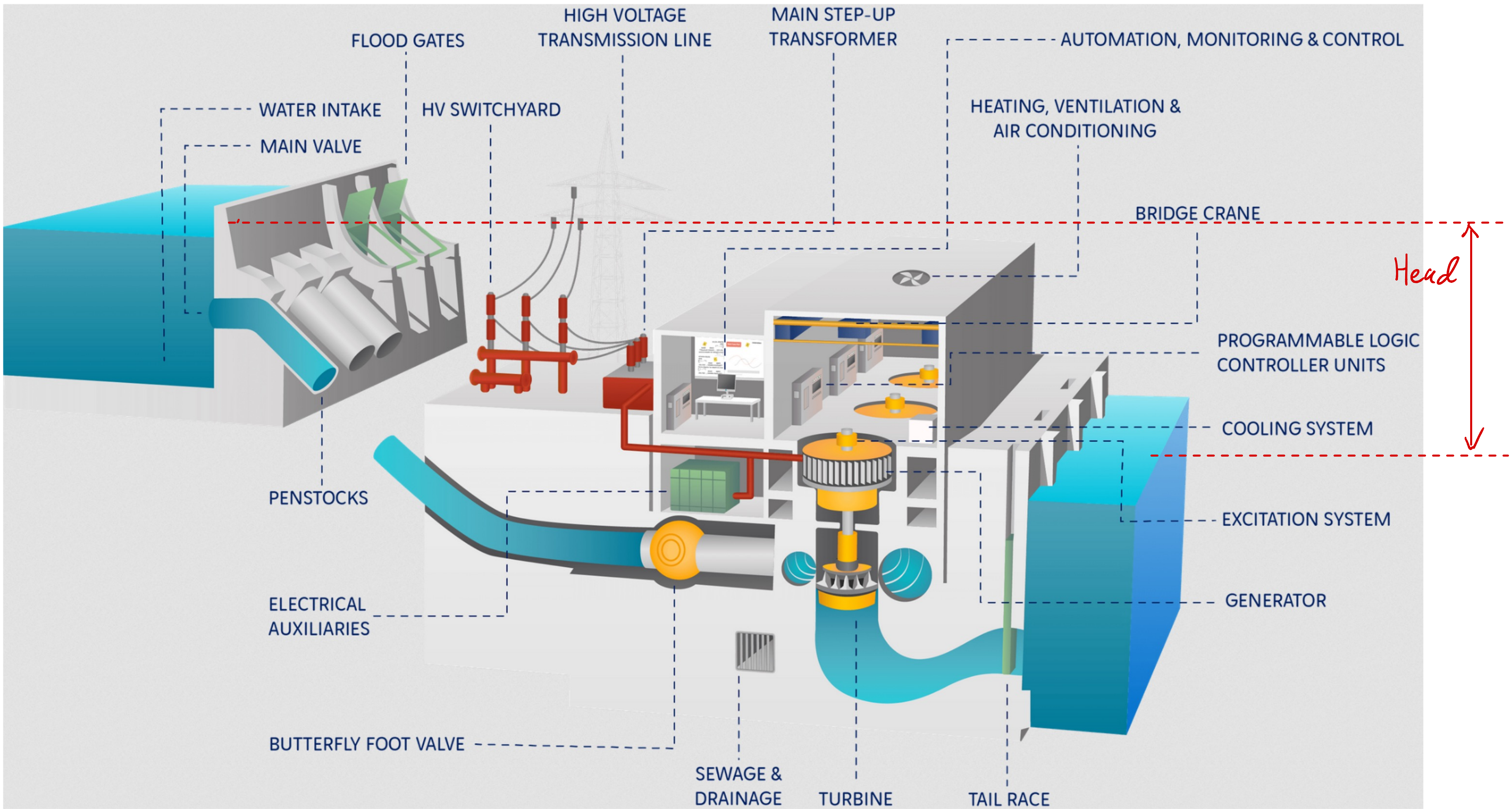
Hydro

Hydropower Characteristics

- Source: potential/kinetic energy from elevated water resulting from hydrologic cycle
- Most widely used form of renewable energy
- Types of conversion processes
  - Diversion (run-of-river)
  - Impoundment
  - Pumped storage

Bonneville Dam: 1,242 MW capacity

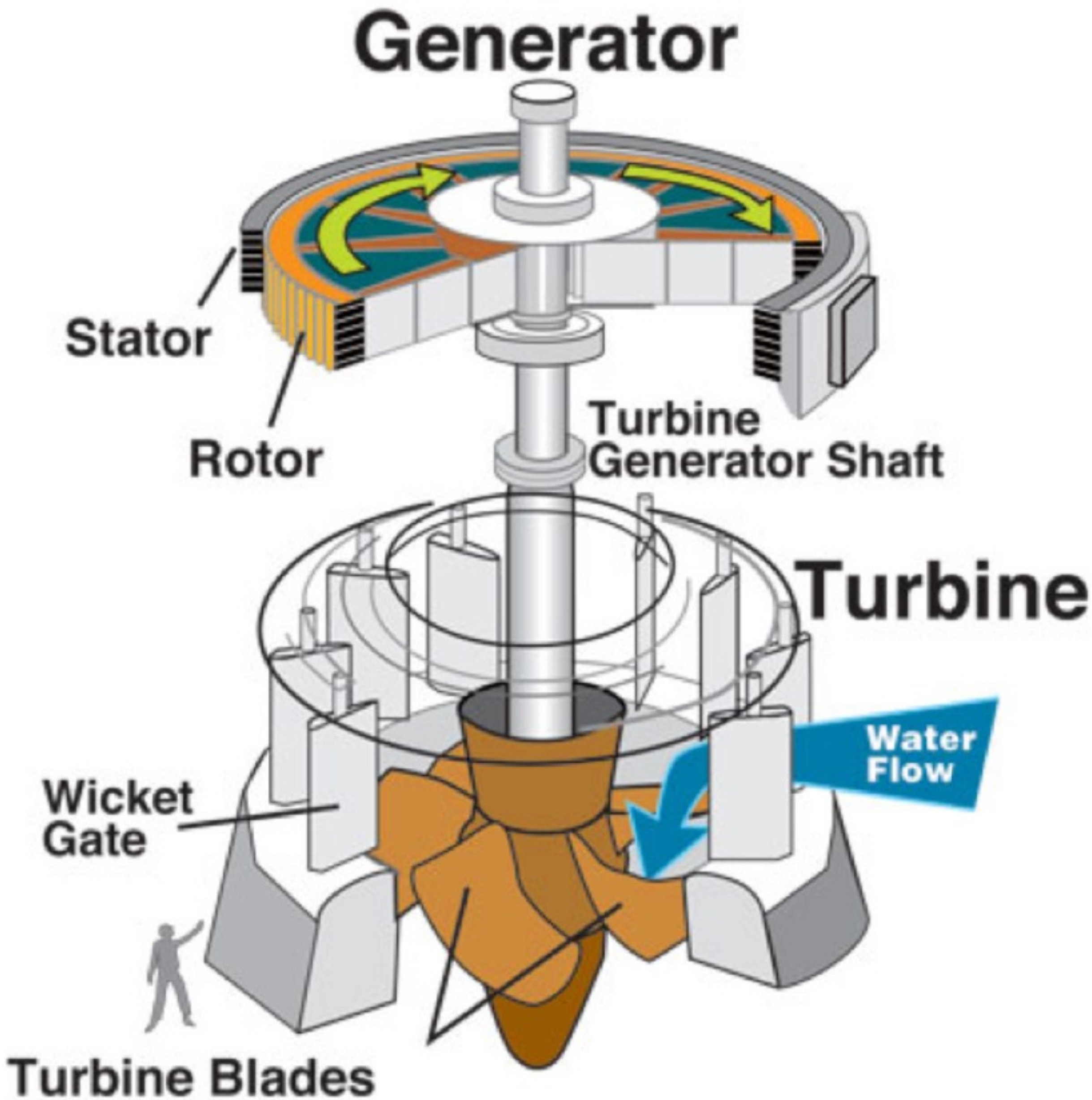
What’s inside a hydro dam?



[https://med.neduet.edu.pk/node/227]

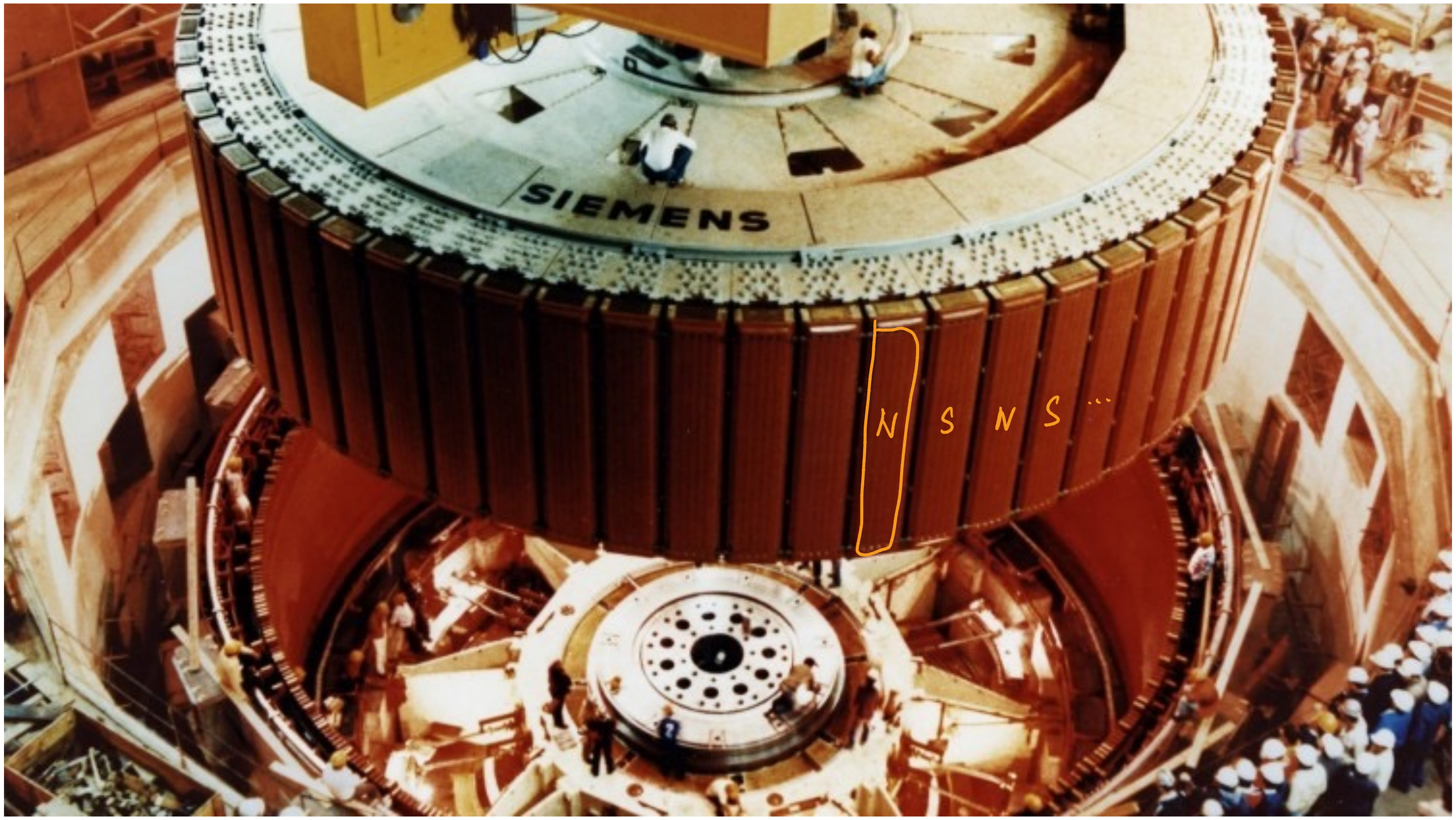
What's inside a hydro dam?

What's inside a hydro dam?

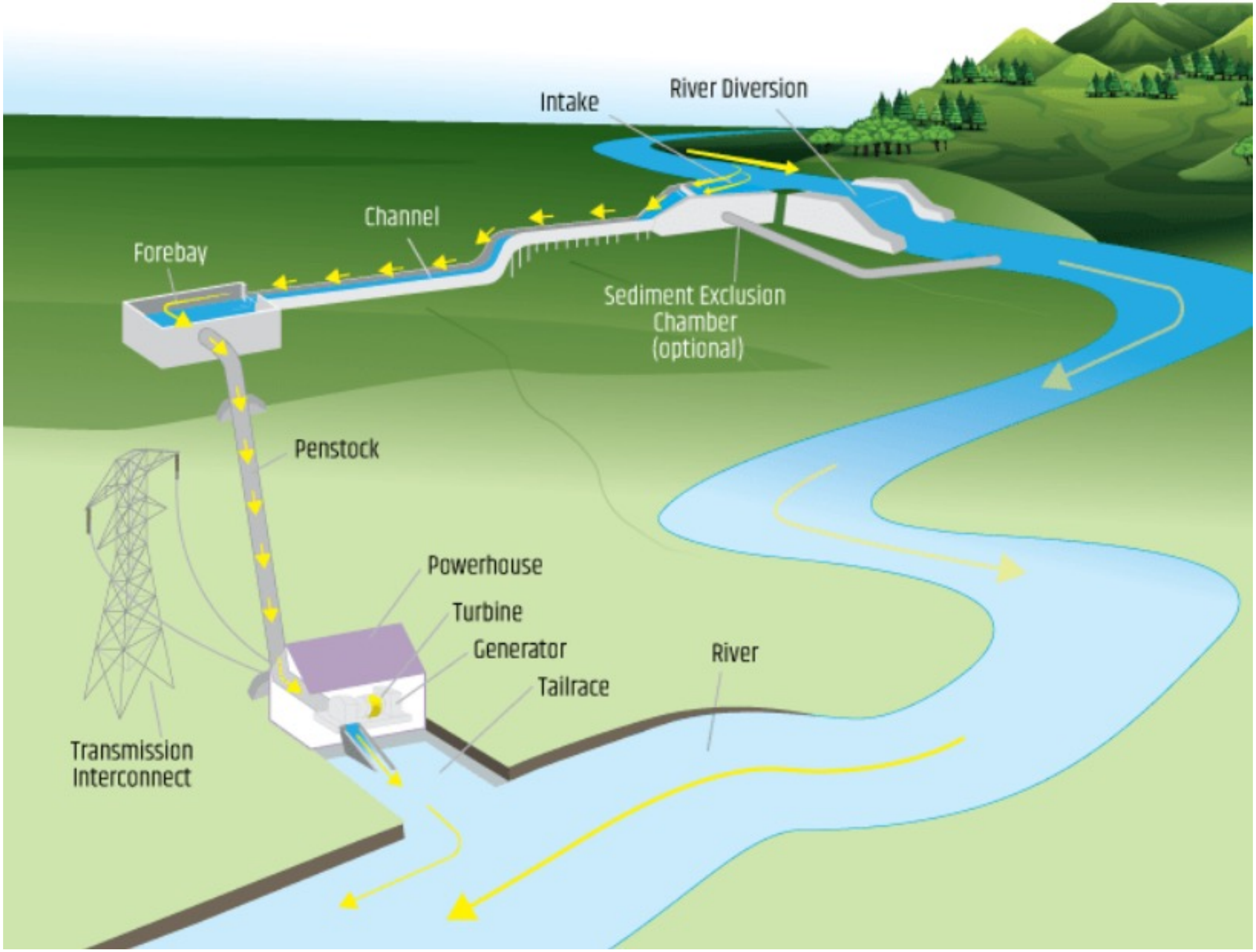


Generator

- Example synchronous wound-rotor
  - 92.3 RPM
  - 78 poles
  - 737 MVA

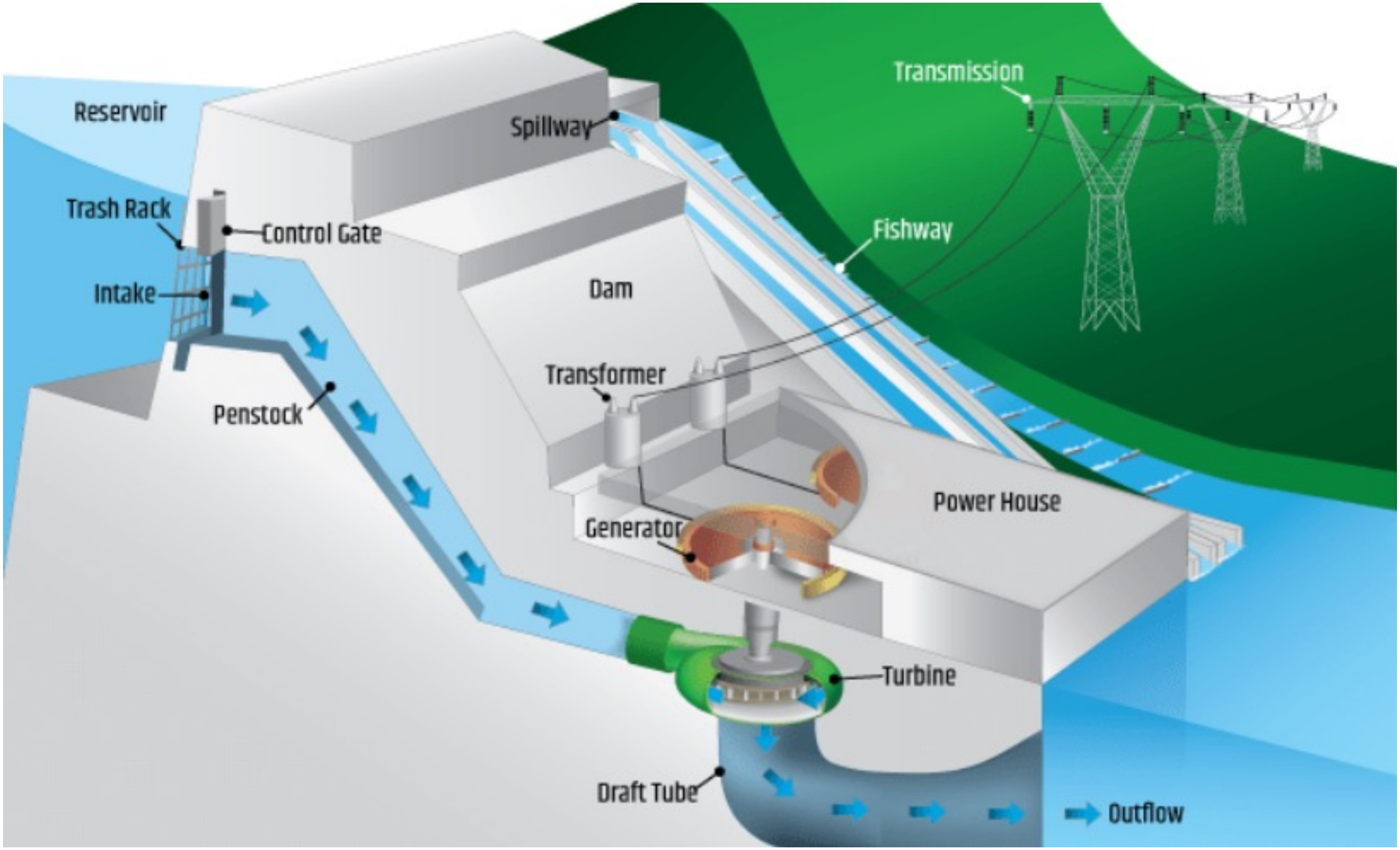


Types of Dams: Diversion (Run of River)



[US DOE]

Types of Dams: Impoundment



[US DOE]

Hydroelectric Power Basics

- Head
  - Water must fall from a higher elevation to a lower one to release its stored energy.
  - The difference between these elevations (the water levels in the forebay and the tailbay) is called head.
- Dams: three categories
  - high-head (800 or more feet)
  - medium-head (100 to 800 feet)
  - low-head (less than 100 feet)
- Power is proportional to the product of head x flow

How hard x How fast

How much energy is in elevated water?

m g h

- Potential energy: mass times acceleration of gravity times height
- $E = \underbrace{\rho\ [kg/m^3] \times \text{volume}\ [m^3]}_{m} \times g\ [m/s^2] \times h\ [m]$
- $P = E/s$

  $= \rho\ [kg/m^3] \times \text{volume/sec}\ [m^3/s] \times g\ [m/s^2] \times h\ [m]$

  $= \rho\ [kg/m^3] \times \text{flow}\ [m^3/s] \times g\ [m/s^2] \times h\ [m]$

  $= \underbrace{\rho\ [kg/m^3] \times g\ [m/s^2]}_{\text{Constant}} \times \underbrace{\text{flow}}_{\text{How fast}}\ [m^3/s] \times \underbrace{h}_{\text{How hard}}\ [m]$
- Power equals constant times how fast (flow) times how hard (height or pressure)
- $P_{turbine} = \overset{\sim 0.8}{\eta} \times \rho\ [kg/m^3] \times g\ [m/s^2] \times \text{flow}\ [m^3/s] \times h\ [m]$

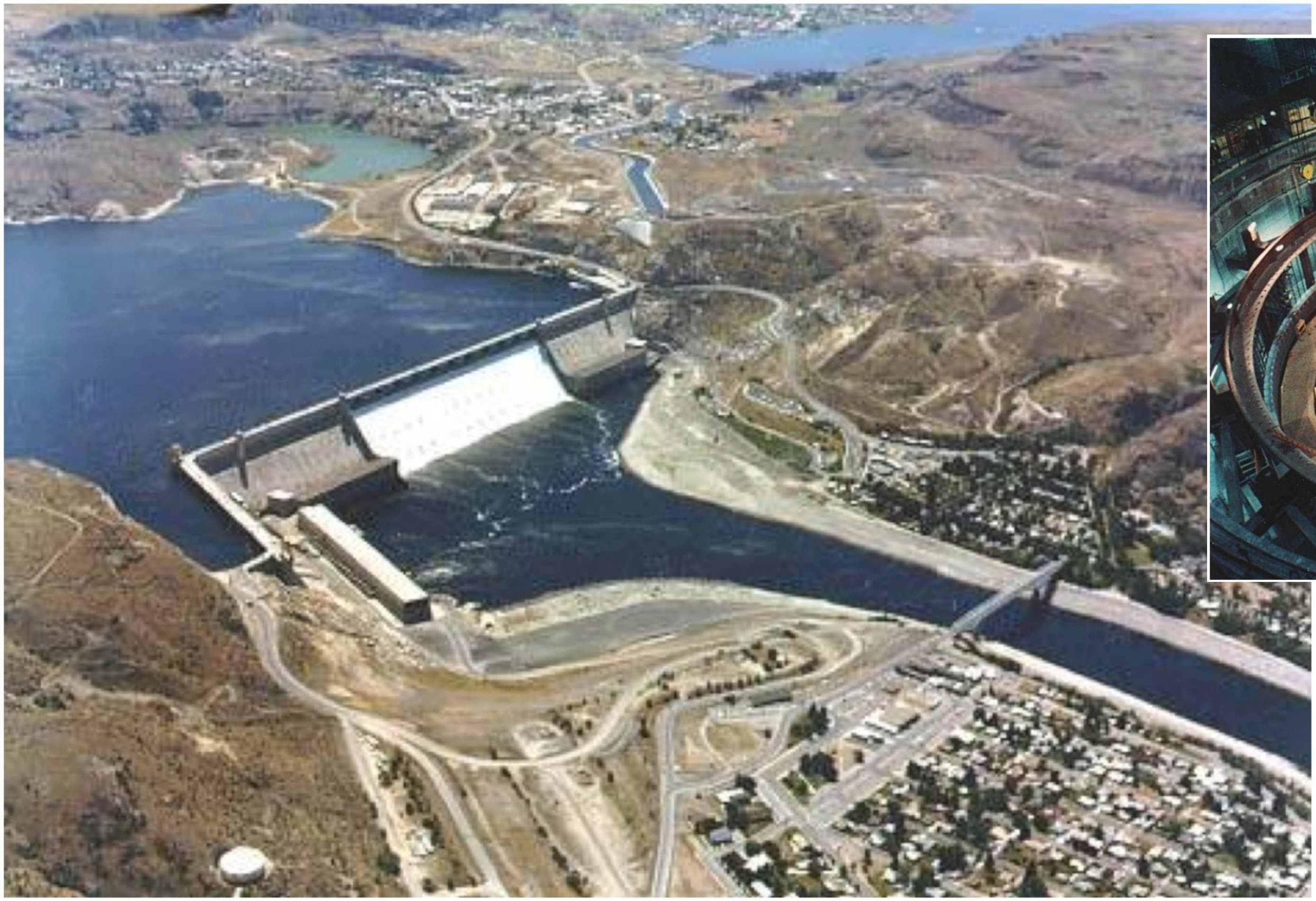
  Where η is the turbine efficiency (typically around 80 %)

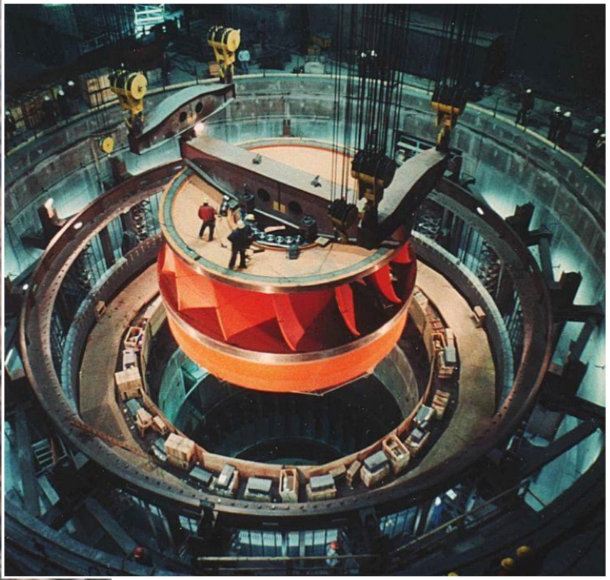
Hydro Project Sizes

- Large
  - >100MW
  - Usually connected to transmission system
- Medium
  - 15-100MW
  - Usually connected to transmission system
- Small
  - 1-15MW
  - Transmission system or distribution system
- Mini
  - 100kW-1MW
  - Typically connected to distribution system or islanded

Large - Grand Coulee Dam

- Installed capacity: 6,809,000 kW
- Pumped hydro capability (for irrigation)





Large - Three Gorges Dam in China

22.5 M homes

- Installed capacity: 22,500,000 kW
- 32 generators 700 MW each

Medium - Detroit and Big Cliff

- Detroit
  - Length: 1,524 ft
  - Height: 463 ft
  - Elevation: 1,580 ft
  - Capacity: 100,000 kW
- Big Cliff
  - Length: 280 ft
  - Height: 191 ft
  - Elevation: 1,212 ft
  - Capacity: 18,000 kW

Big Cliff Dam

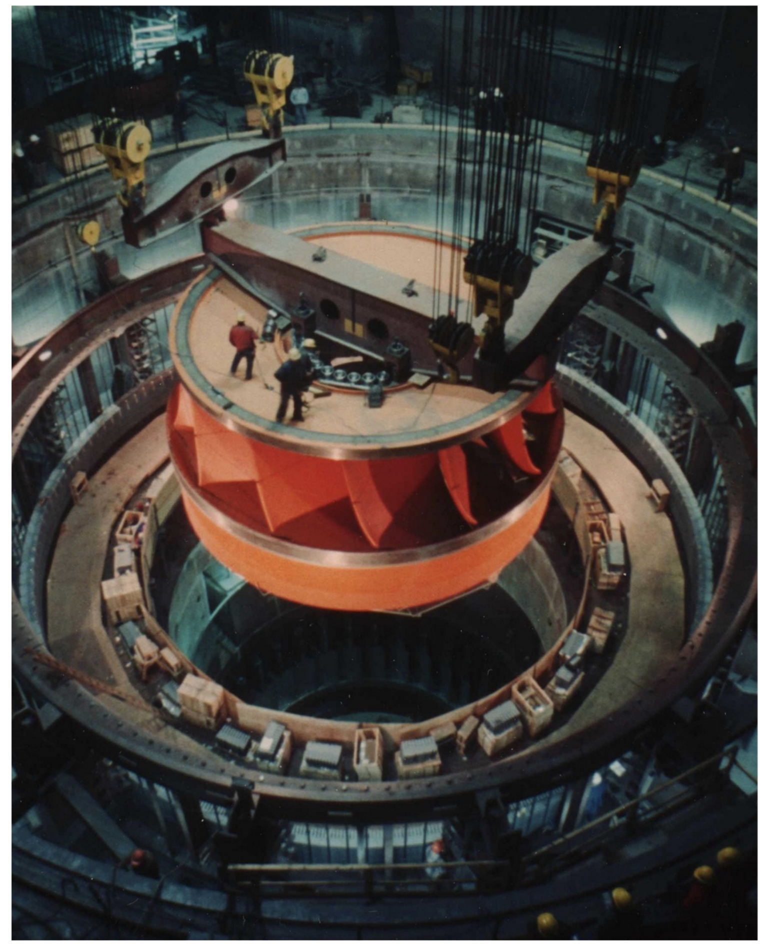
Mini - Ashland Reeder Gulch Hydro

- 845 kVA generator
- Pelton turbine
- High head run-of-river
- Extracts potential energy from city water supply

Hydro Turbines: Francis

Reaction turbine

- Reaction turbine
- Converts pressure drop to force on the turbine
- Guide vanes or wicket gate adjust flow



Hydro Turbines: Kaplan

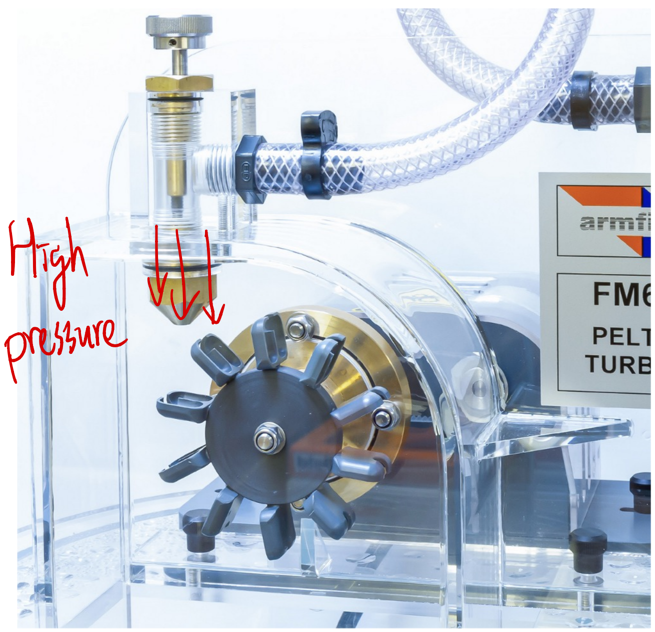
High Flow

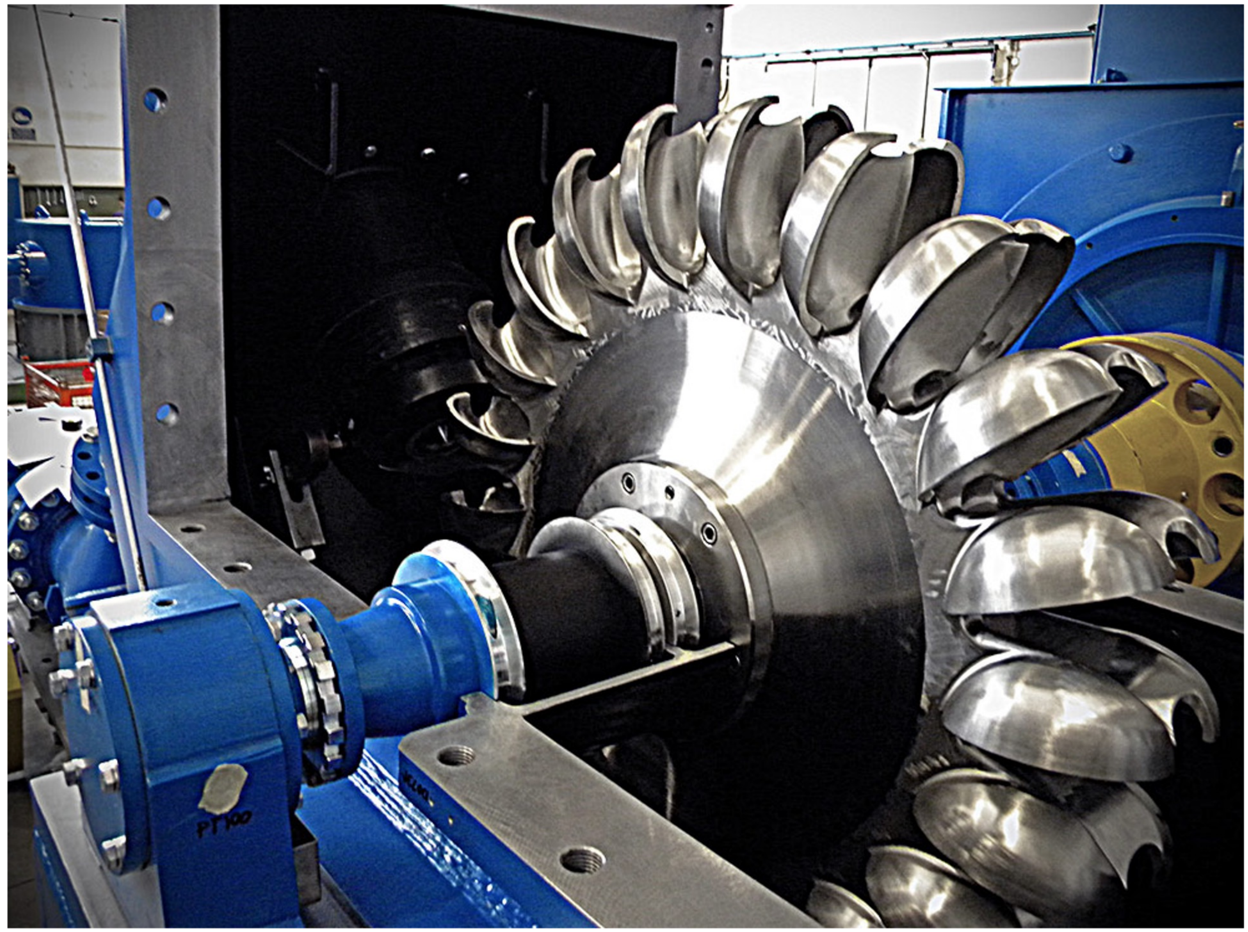
Hydro Turbines: Pelton

High Head

- Impulse turbine
- Converts water pressure to high velocity to impulse on paddle

High pressure



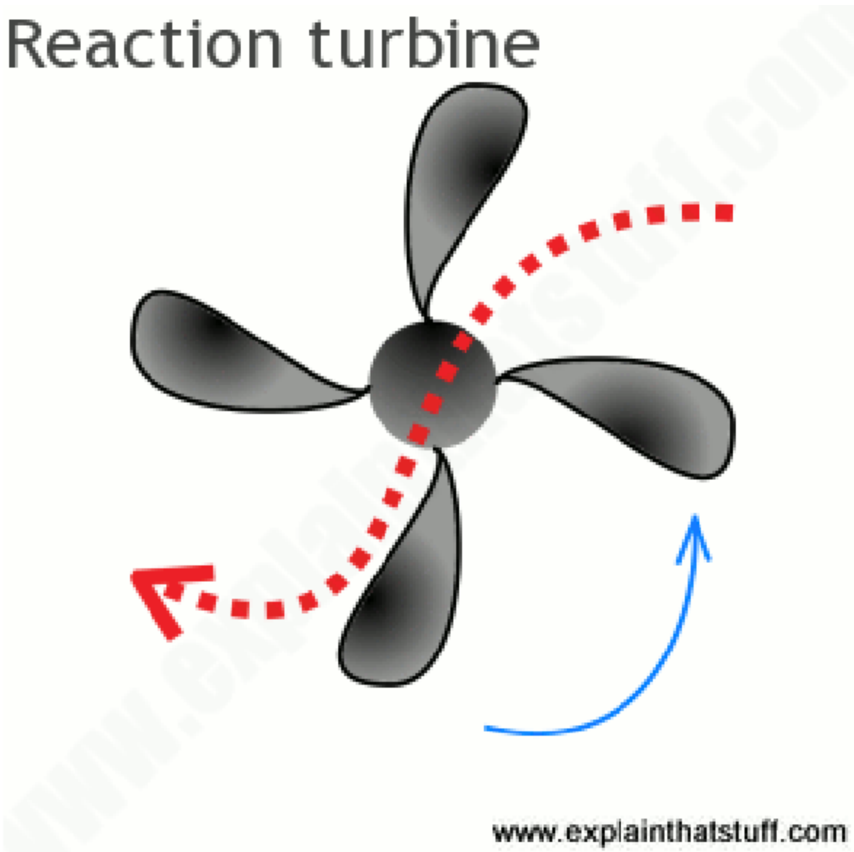


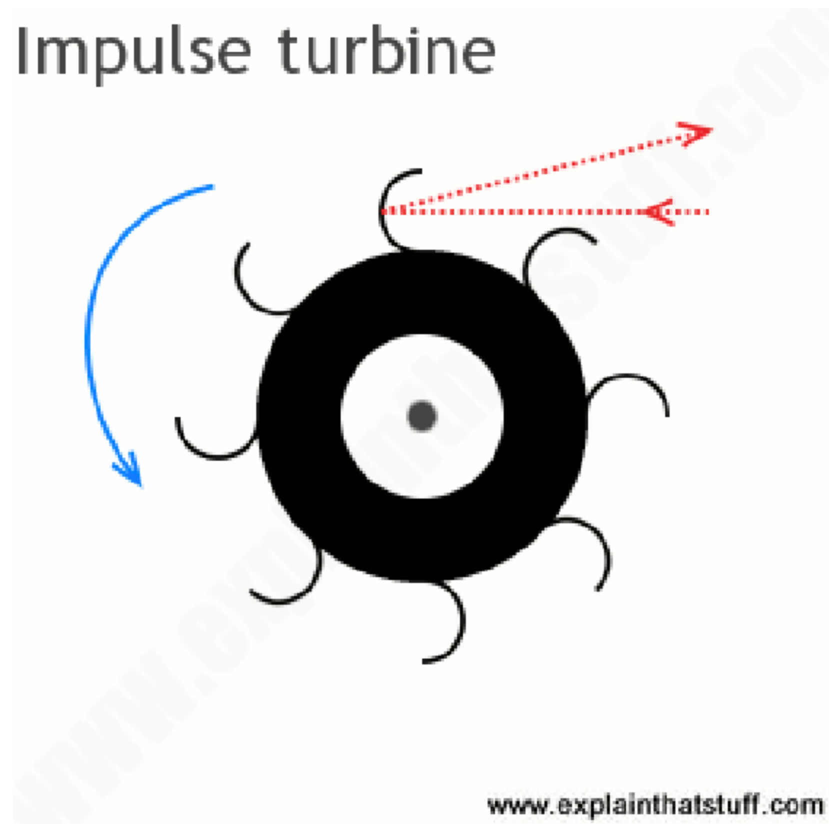
Reaction vs Impulse Turbine

Don't change speed but change pressure (Pressure Difference → Energy)

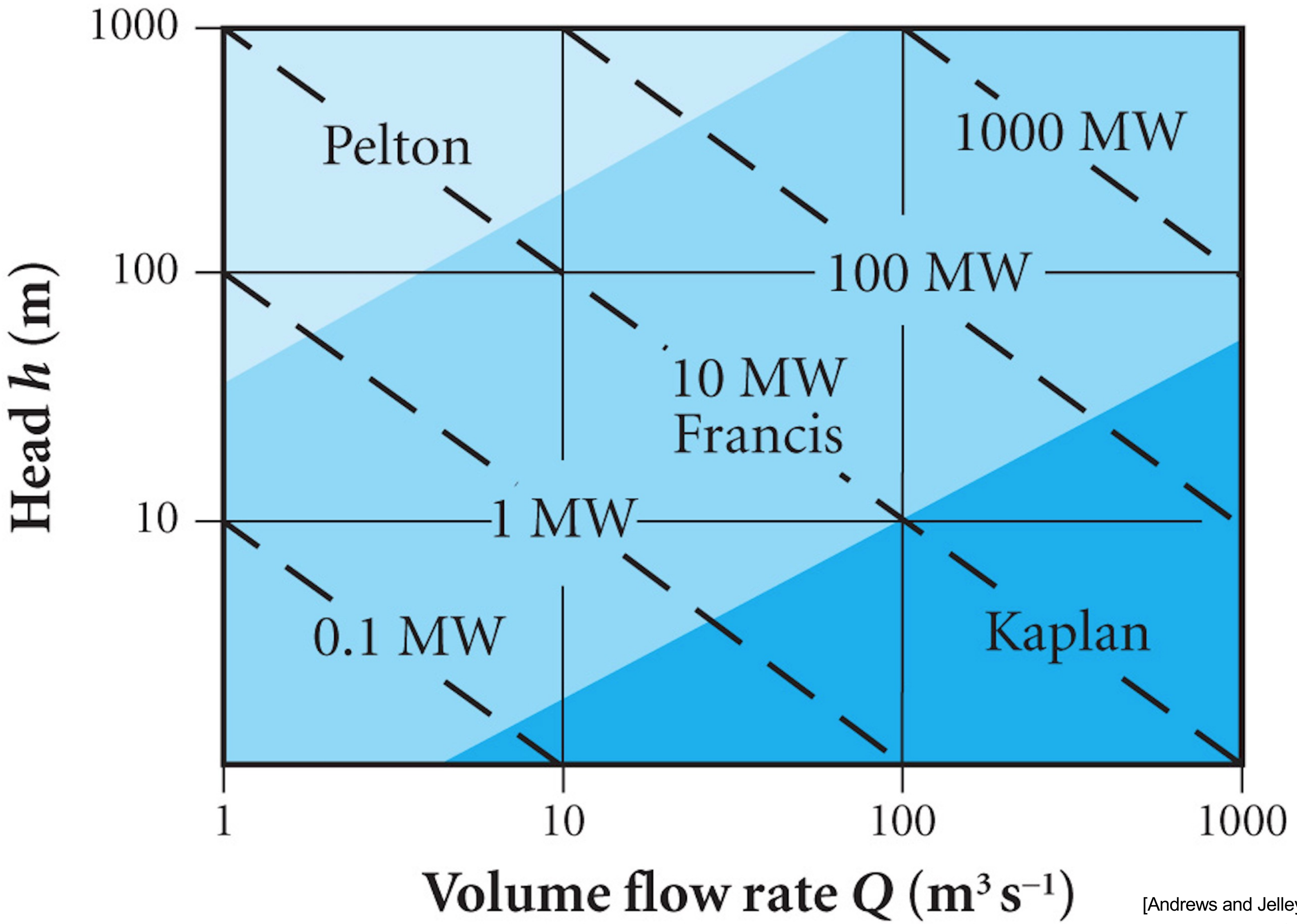
- Francis and Kaplan turbine: reaction; pressure drops across the turbine
- Pelton: impulse; converts kinetic energy to force * time (impulse)

High Pressure





When to use what type of turbine?



[Andrews and Jelley]

High elevation (head) or high flow?

Hoover Dam: impoundment

The Dalles Dam: run of river

What are the top hydro countries?

Ten of the largest hydroelectric producers as at 2020.[56]

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of world's production	% in domestic electricity generation
China	1232	352	0.37	28.5%	17.2%
Brazil	389	105	0.56	9.0%	64.7%
Canada	386	81	0.59	8.9%	59.0%
United States	317	103	0.42	7.3%	7.1%
Russia	193	51	0.42	4.5%	17.3%
India	151	49	0.43	3.5%	9.6%
Norway	140	33	0.49	3.2%	95.0%
Japan	88	50	0.37	2.0%	8.4%
Vietnam	84	18	0.67	1.9%	34.9%
France	71	26	0.46	1.6%	12.1%

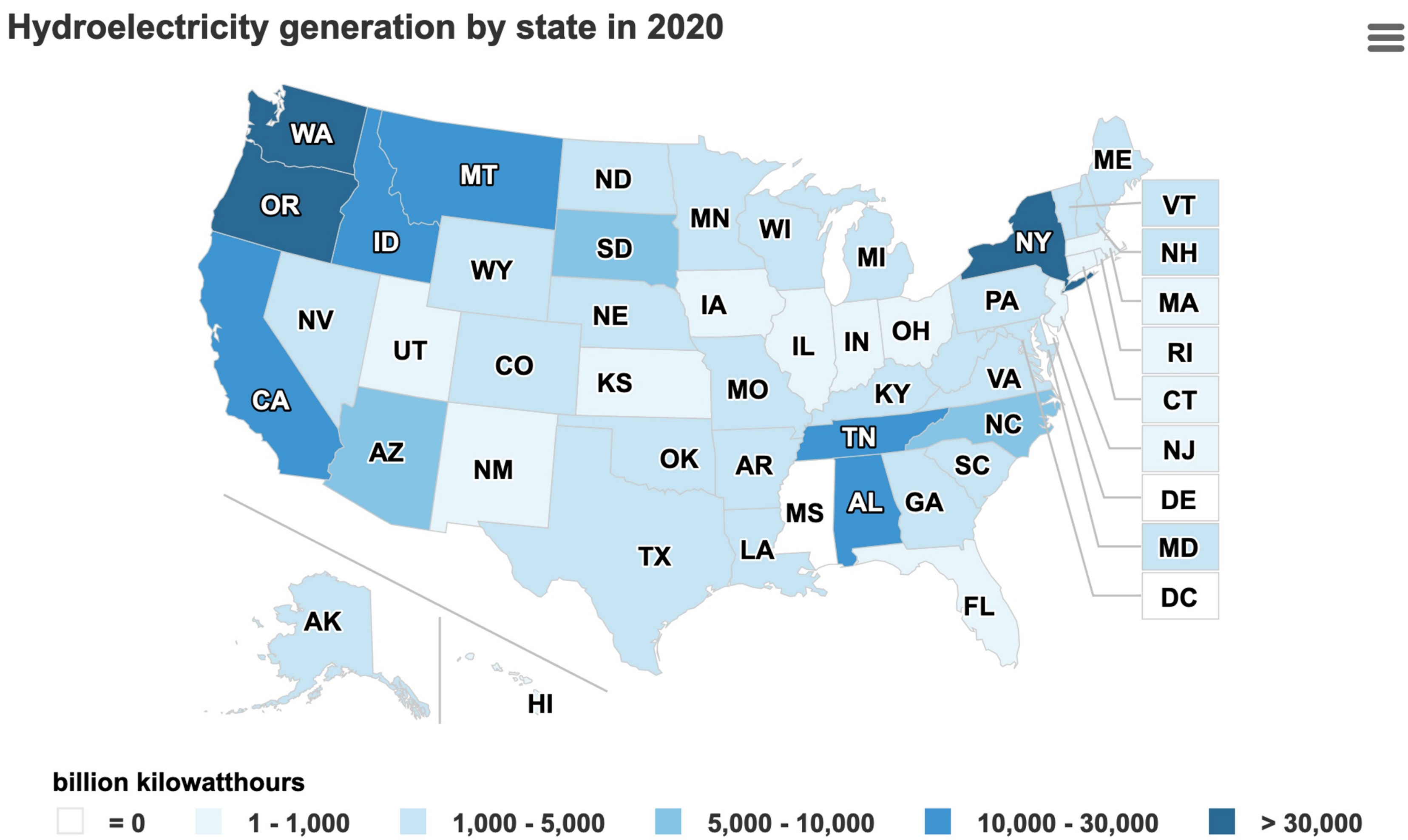
[Wikipedia]

Top 10 Projects

Name	Country	River	Installed capacity (MW)	Annual production (TW-hour)[note 1]	Area flooded (km²)	Reservoir volume (km^3)[6]	Years of completion
Three Gorges Dam	China	Yangtze	22,500	111.8 [7]	1,084	39.3	2008/2012
Itaipu Dam	Paraguay Brazil	Paraná	14,000	103 [1]	1,350	29	1984/1991, 2003[note 2]
Xiluodu	China	Jinsha	13,860[8]	55.2		12.67	2014[9]
Belo Monte	Brazil	Xingu	11,233[10]	39.5	441	1.89	2016-2019
Guri	Venezuela	Caroní	10,235	53.41	4,250	135	1978, 1986
Wudongde	China	Jinsha	10,200	39		7.4	2020/2021[11]
Tucuruí	Brazil	Tocantins	8,370	41.43	3,014	45	1984, 2007
Grand Coulee	United States	Columbia	6,809	20[12]	324	12	1942/1950, 1973, 1975/1980, 1983/1984, 1991[note 3]
Xiangjiaba	China	Jinsha	6,448	30.7	95.6	5.16	2014[13]
Longtan Dam	China	Hongshui	6,426	18.7[14]		27.27	2007/2009

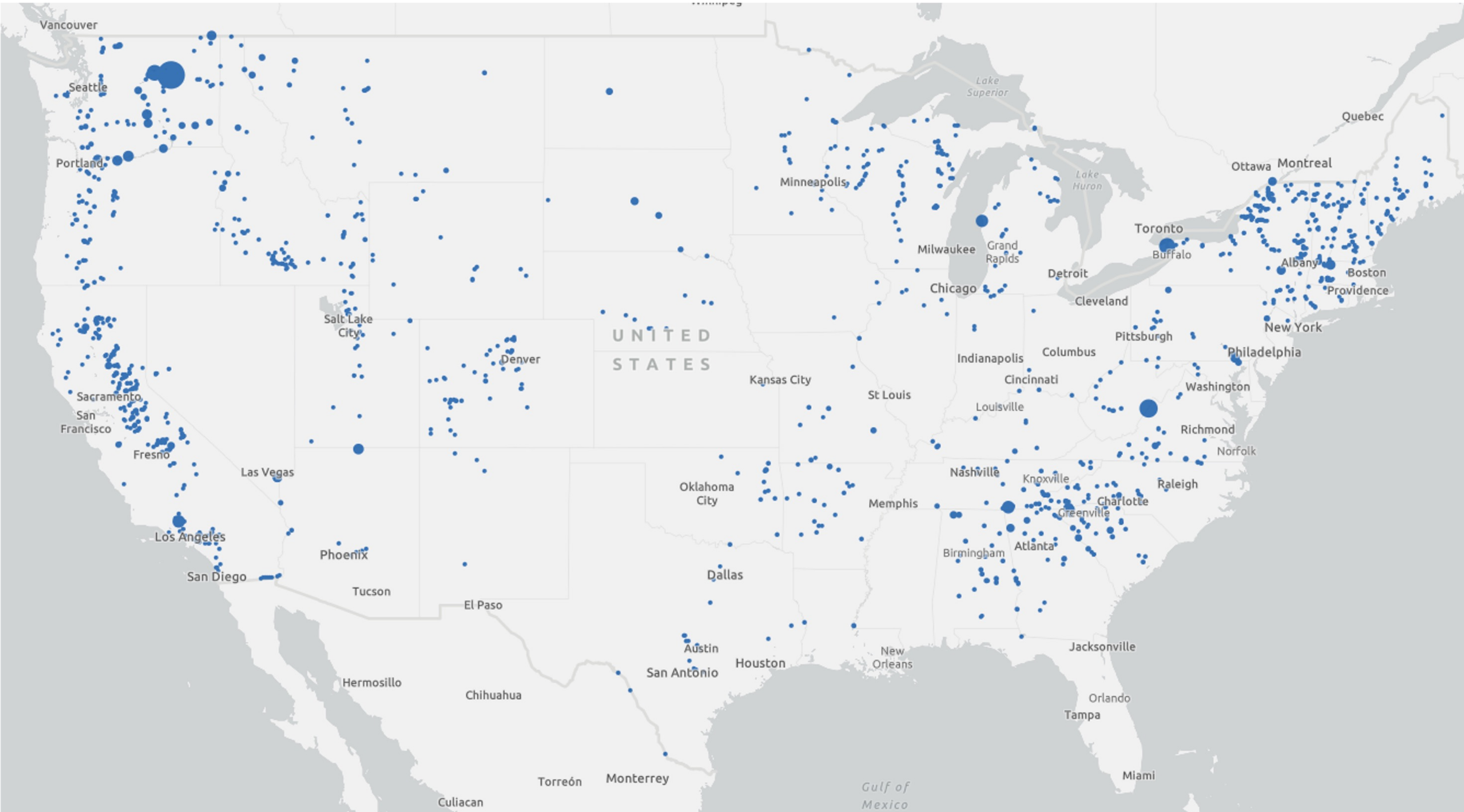
[Wikipedia]

What states have the most hydroelectric power?



Note: Includes utility-scale conventional hydropower.
Source: U.S. Energy Information Administration, *Electric Power Monthly*, Table 1.10.B, February 2021, preliminary data

Where are the hydro projects in the US?



Dams of the Columbia River Basin

Columbia River Top 10

Rank	Name	Cap. (MW)	Location	Date Auth.	Date Comp.	Lake Formed
1	Grand Coulee Dam	6,809	WA	1933	1951	Roosevelt Lake, Banks Lake
2	Chief Joseph Dam	2,620	WA	1946	1955	Rufus Woods Lake
3	John Day Dam	2,160	WA/OR	1958	1971	Lake Umatilla
4	Revelstoke Dame	1,980	BC	1964	1984	Revelstoke Lake
5	Mica Dam	1,805	BC	1964	1973	Kinbasket Lake
6	The Dalles Dam	1,780	WA/OR		1960	Lake Celilo
7	Rocky Reach Dam	1,287	WA	1956	1961	Lake Entiat
8	Bonneville Dam	1,050	WA/OR		1937	Lake Bonneville
9	Wanapum Dam	1,038	WA			Lake Wanapum
10	McNary Dam	980	WA/OR	1941	1954	Lake Wallula

John Day Dam

The Dalles Dam

What are the functions of dams?

The dams provide

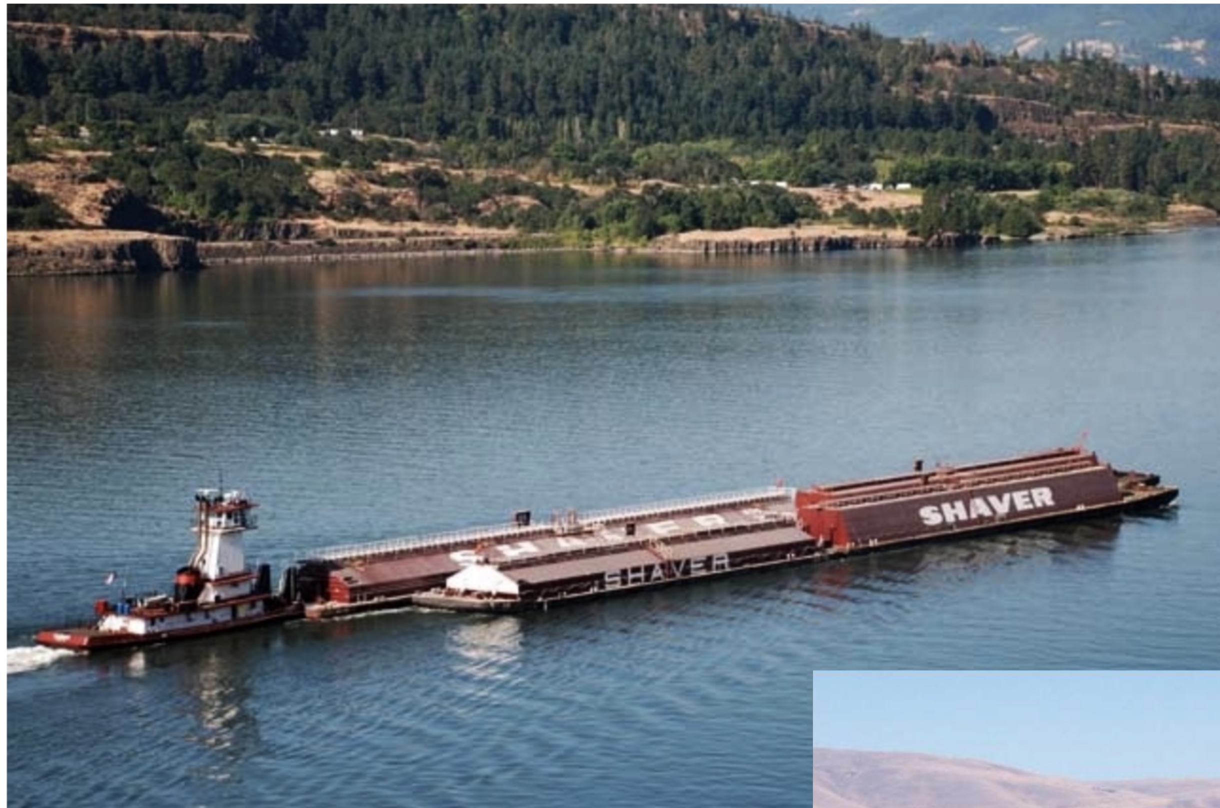
- Flood control
- Irrigation
- Recreation
- Fish passage
- Shipping (locks)
- Power

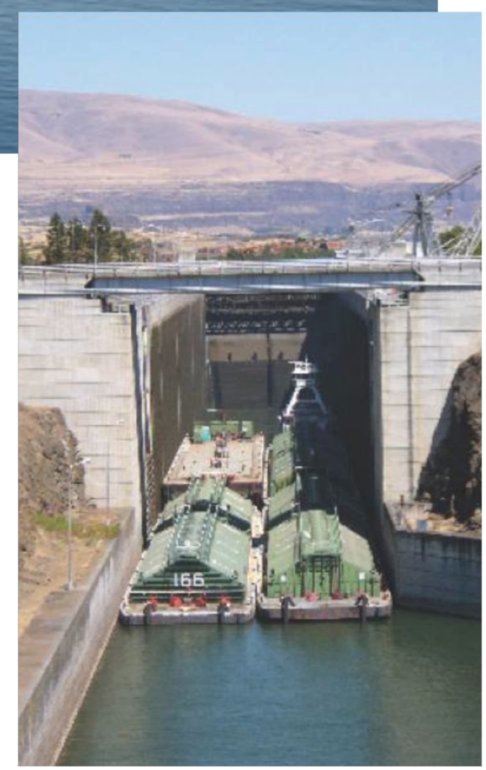
Shipping

- Approximately 1000 semi-trucks worth of freight are carried by barge on the Columbia river every day.
- Each barge can carry about 1,500 tons of cargo, vs about 25 tons per semi truck.
- The efficiency of barge shipping is about 500 miles/gallon/ton of cargo, vs about 50 miles/gallon/ton of cargo in semi-truck.

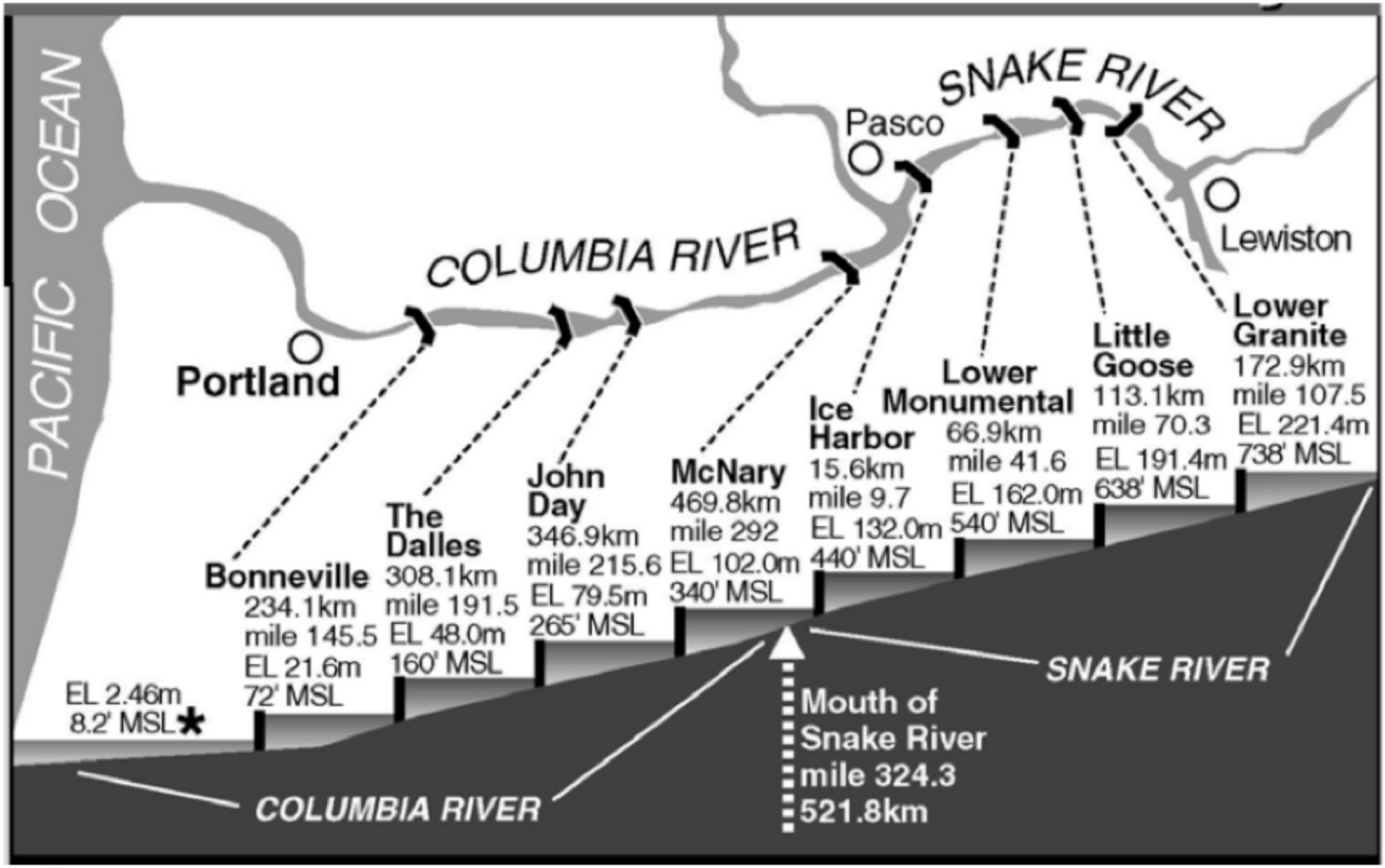
[https://www.bendbulletin.com/business/broken-columbia-river-barge-lock-means-commerce-chokehold/article_ad319535-2ad1-59e1-9d61-7ef35d528d5c.html]

[https://www.tenntom.org/shipping-comparisons/]



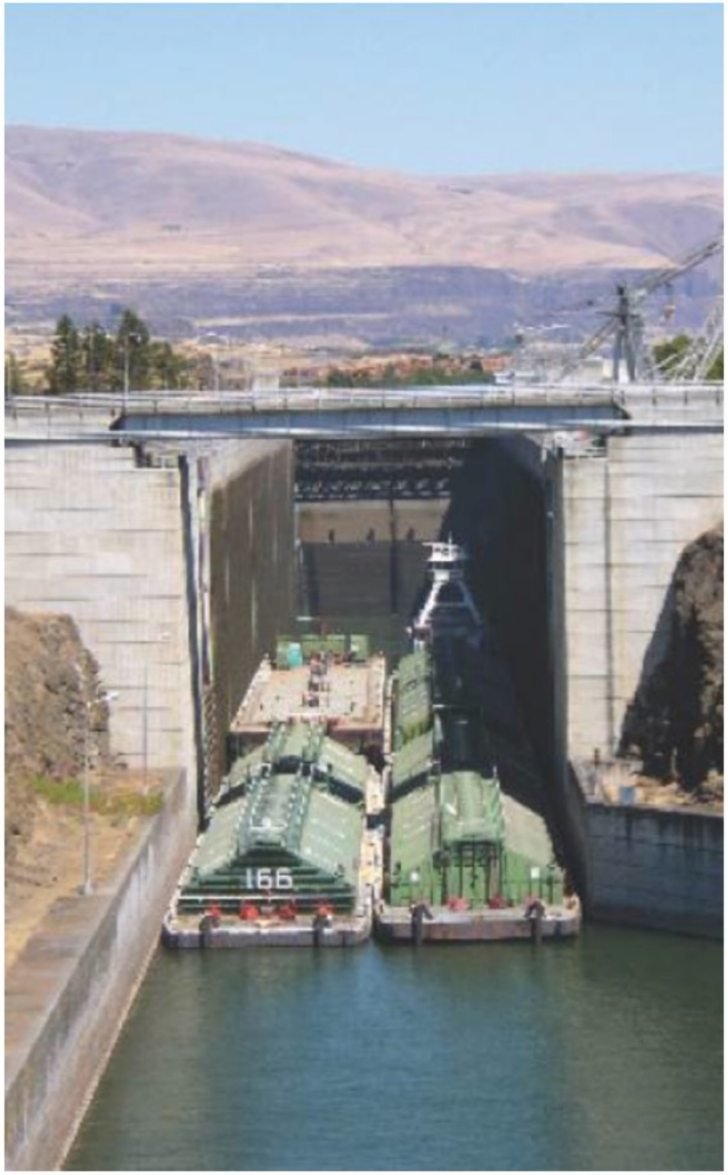


Columbia River Locks



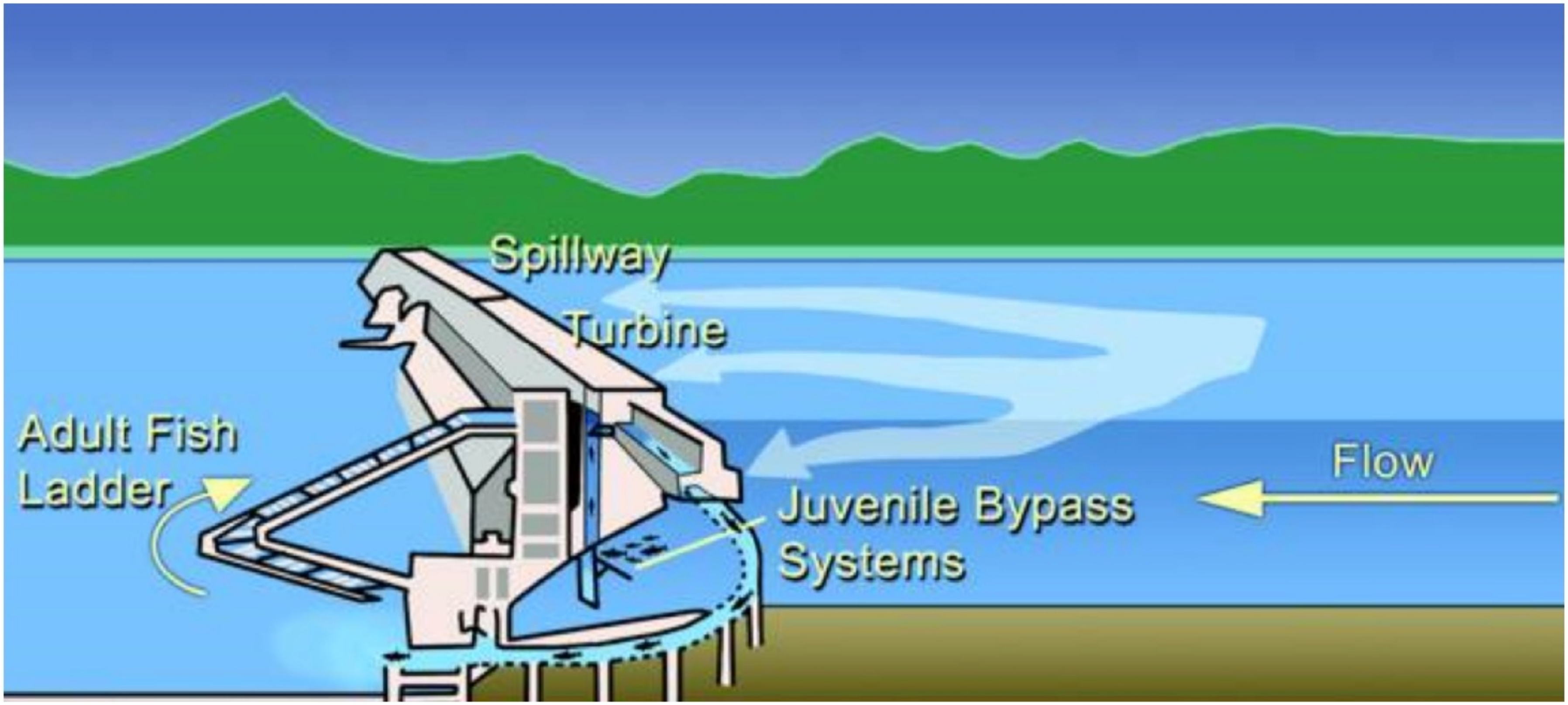
[USACE brochure "How to Lock Through"]

Columbia River Locks



[Jim Shaw, Pacific Maritime, June 2006]

Fish Migration



[http://www.nwcouncil.org/library/2003/2003-20/hydro.htm]

What about CO_2?

- No CO_2 associated with electricity production.
- There is CO_2 associated with dam building, and with decaying plant matter in the reservoir.
- "Small run-of-the-river plants emit between 0.01 and 0.03 pounds of carbon dioxide equivalent per kilowatt-hour. Life-cycle emissions from large-scale hydroelectric plants built in semi-arid regions are also modest: approximately 0.06 pounds of carbon dioxide equivalent per kilowatt-hour. However, estimates for life-cycle global warming emissions from hydroelectric plants built in tropical areas or temperate peatlands are much higher. After the area is flooded, the vegetation and soil in these areas decomposes and releases both carbon dioxide and methane. The exact amount of emissions depends greatly on site-specific characteristics. However, current estimates suggest that life-cycle emissions can be over **0.5 pounds of carbon dioxide equivalent per kilowatt-hour**.
- To put this into context, estimates of life-cycle global warming **emissions for natural gas generated electricity are between 0.6 and 2 pounds of carbon dioxide equivalent per kilowatt-hour and estimates for coal-generated electricity are 1.4 and 3.6 pounds of carbon dioxide equivalent per kilowatt-hour**." [Union of Concerned Scientists, https://www.ucsusa.org/resources/environmental-impacts-hydroelectric-power]

Pumped Hydro

- Bath County Pumped Storage Station, Virginia
- Power capacity of 3,000 MW
- Energy capacity of 24,000 MWh
- 380 meters elevation difference
- Pumped hydro is presently the only technology feasible for very large scale (i.e., grid scale) energy storage.

Hydro Pros and Cons

PROS

- Emissions-free operation, with virtually no CO2, NOX, SOX, hydrocarbons, or particulates (during operation)
- Renewable resource with high conversion efficiency to electricity (80+%)
- Dispatchable with storage capacity
- Usable for base load, peaking and pumped storage applications
- Scalable from 10 kW to 20,000 MW
- Low operating and maintenance costs
- Long lifetimes

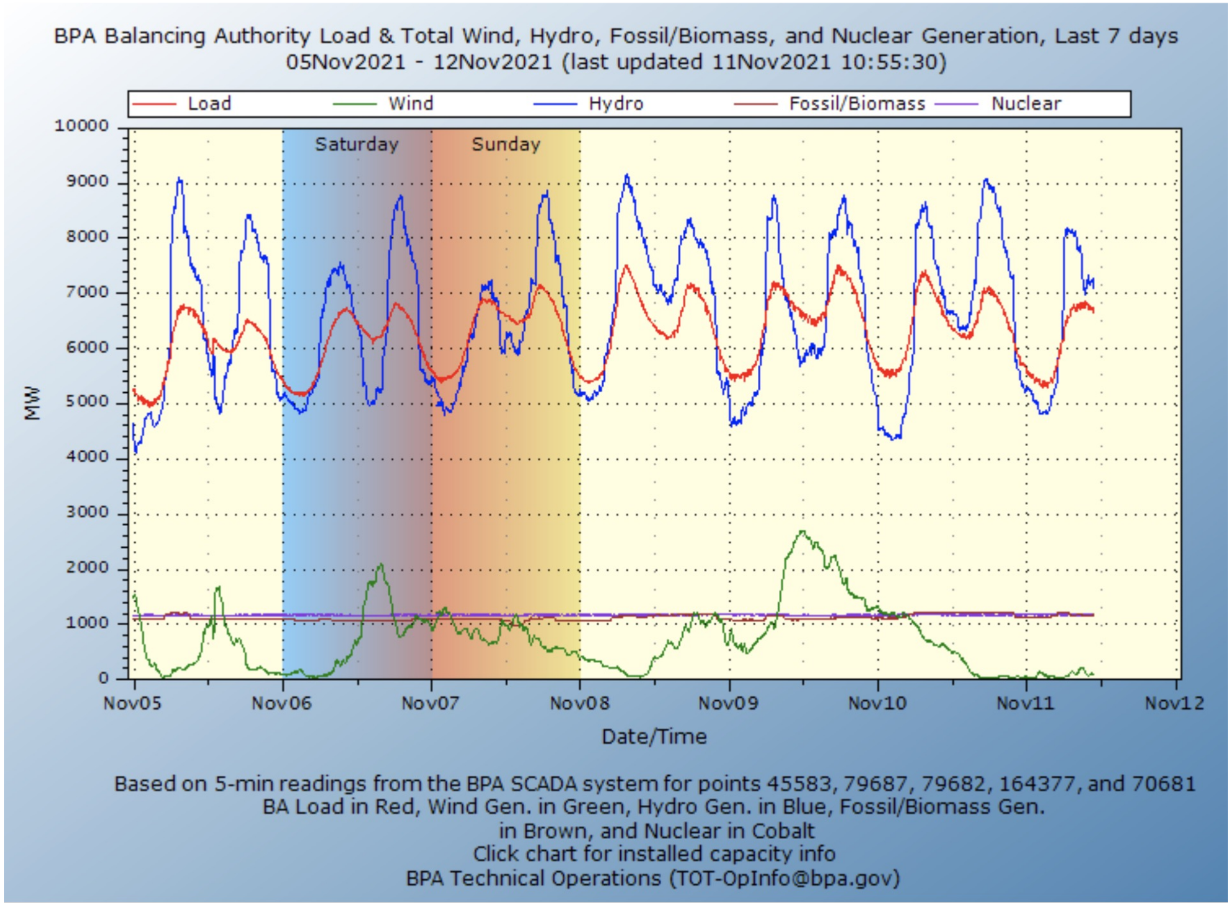
CONS

- Frequently involves impoundment of large amounts of water with loss of habitat due to land inundation, with some emissions
- Annually variable output – dependent on rainfall and snowfall
- Impacts on river flows and aquatic ecology, including fish migration and oxygen depletion
- Social impacts of displacing indigenous people
- Health impacts in developing countries
- High initial capital costs
- Long lead time in construction of large projects

What are the characteristics of hydropower?

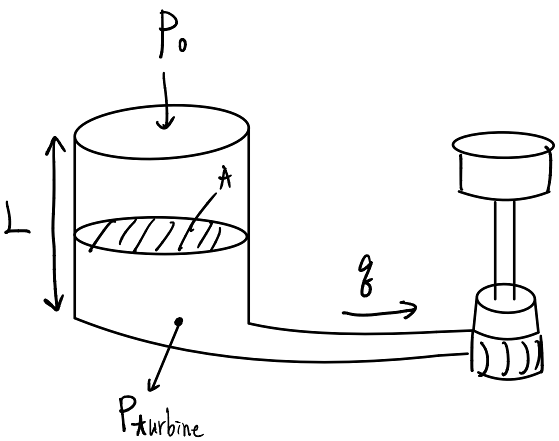
Reserve and baseload characteristics:

- Rapid rate of change (W/s) for load and renewable following
- A large area under the curve (W x s = J)



Hydro Modeling

- Modeling done in mechanical per unit (normalized)



$$\overbrace{L\cdot A\cdot \rho\cdot g}^{\text{Mass}\times\text{force}} + \overbrace{P_0\cdot A}^{\text{force on the top}} - \overbrace{P_t\cdot A}^{\text{force of bottom}} = \overset{m}{L}\,\overset{m^2}{A}\cdot\overset{Kg/m^3}{\rho}\cdot\overset{m/s^2}{\dot V}$$

$$= L\cdot\rho\cdot\underbrace{\dot q}_{\text{acceleration of flow}}$$

amerzphere pressure standard

$$L + \frac{\cancel{P_0}^{\,0} - P_t}{\rho g} = \frac{L}{A g}\cdot\dot q$$

$$[m] + \underbrace{\left[\frac{\cancel{N}}{\cancel{m^2}}\right]\left[\frac{m^3}{\cancel{Kg}}\right]\left[\frac{\cancel{Kg}}{\cancel{N}}\right]}_{=[m]}$$

$$\rightarrow \frac{h_{base}}{h_{base}}(h + h_t) = \left(\frac{L}{A g}\cdot\dot q\right)\cdot\frac{q_{base}}{q_{base}}$$

$$\rightarrow h_{pu} + h_{t.pu} = \underbrace{\left(\frac{L}{A g}\cdot\frac{q_{base}}{h_{base}}\right)}_{T_W}\dot q_{pu}$$

Hydro Modeling: Equation Summary

① $$h_{pu} - h_{t,pu} = T_w \cdot \dot{q}_{pu}$$

② $$P_{t,pu} = h_{t,pu} \times q_{pu}$$

③ $$h_{t,pu} = \left(\frac{q_{pu}}{G}\right)^2 \qquad \begin{cases} G = 1, & \text{gate open} \\ G = 0, & \text{gate closed} \end{cases}$$

How open is the gate