Hydro-Electric Power

Hoover Dam (near Las Vegas, NV)
Arch-gravity dam. Black Canyon/Colorado River.
2.1 GW, (4-10)TWh, construction 1931-1936,
5y, $49M(1930)→$750M, >>100Ŧ

Agenda

- Hydroelectric energy resources,
  - Hydrological cycle,
  - Seasonal, climatic trends,
  - Schematics & types of hydroelectric plants,
- Operational principles of hydro power plants,
  - Ideal fluid dynamics laws,
  - Energy & momentum transfer,
  - Hydro turbine types,

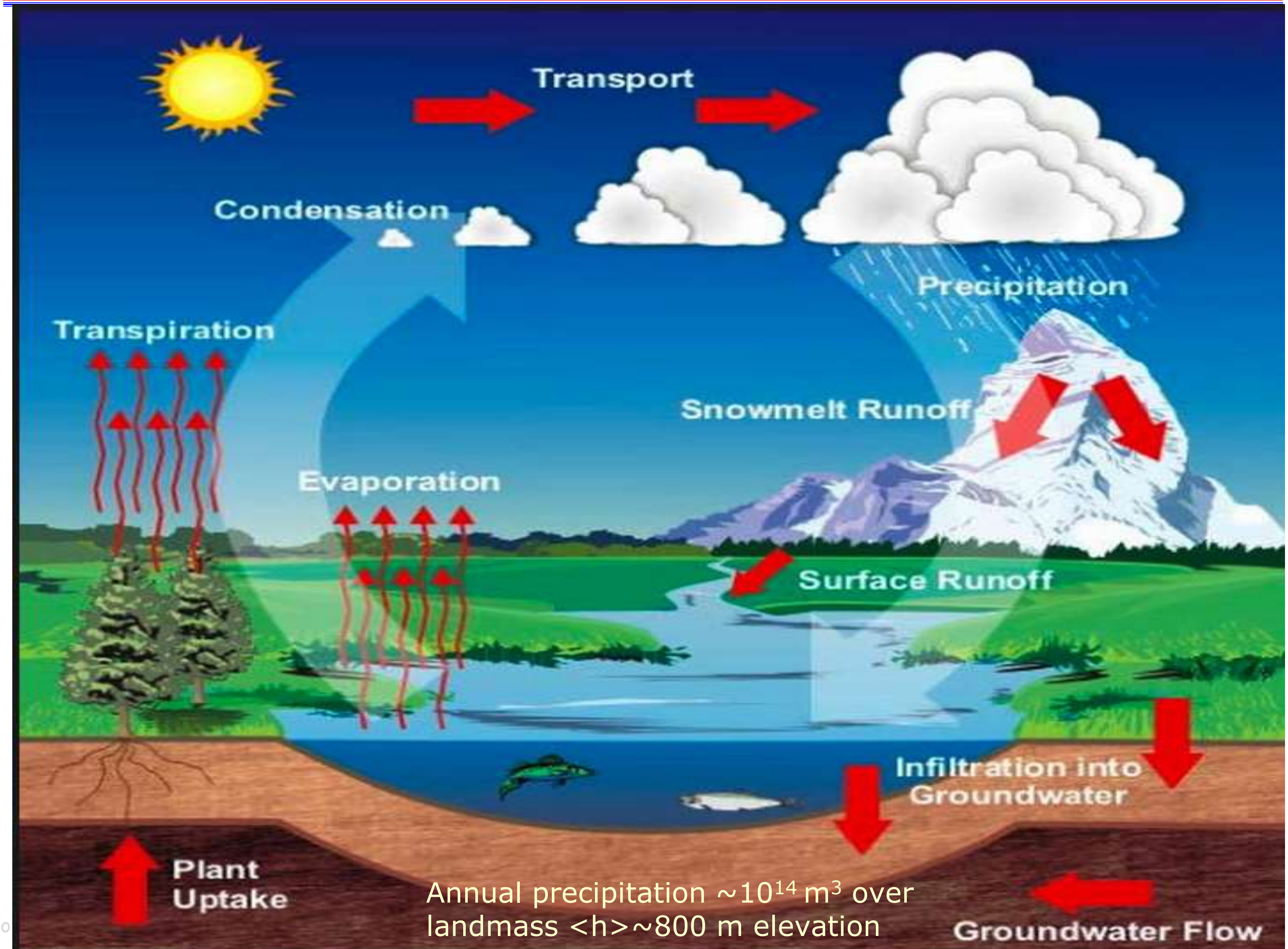
- World/US hydro-electricity generation,
  - Construction cost, electricity price,
  - Consumption,

- Major US and World hydro-electric dam projects,
- Strategic issues of hydro-electric energy production,
  - ecological impact, emissions,
  - non-renewable aspects.

- Next topic: Power from Biomass

Reading Assignments
A&J Ch. 4, 5.1-5.7
LN 3.2

The Hydrological Cycle

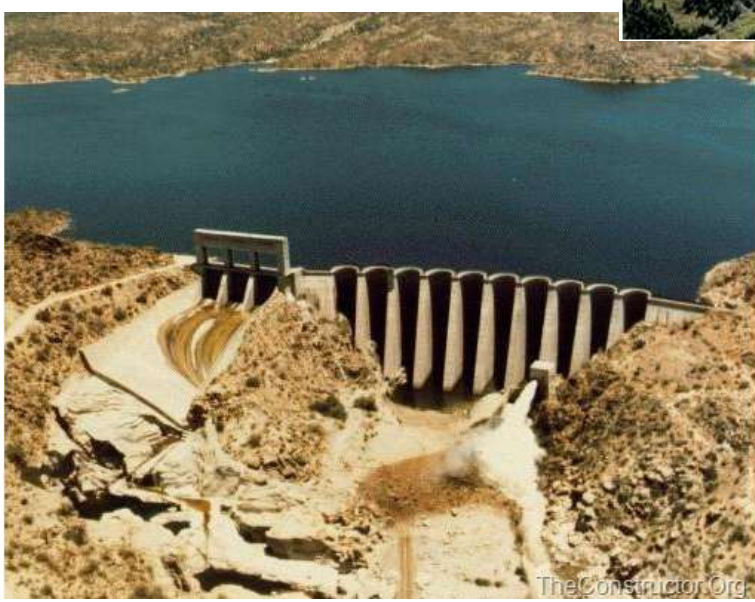


Annual precipitation ~10^{14} m^3 over landmass <h>~800 m elevation

Hydroelectric Plant Reservoir/Dam Architecture

High-head dam:
Grande Dixence (Val des Dix, Switzerland), 285 m high dam, collects melt from Alpine glaciers

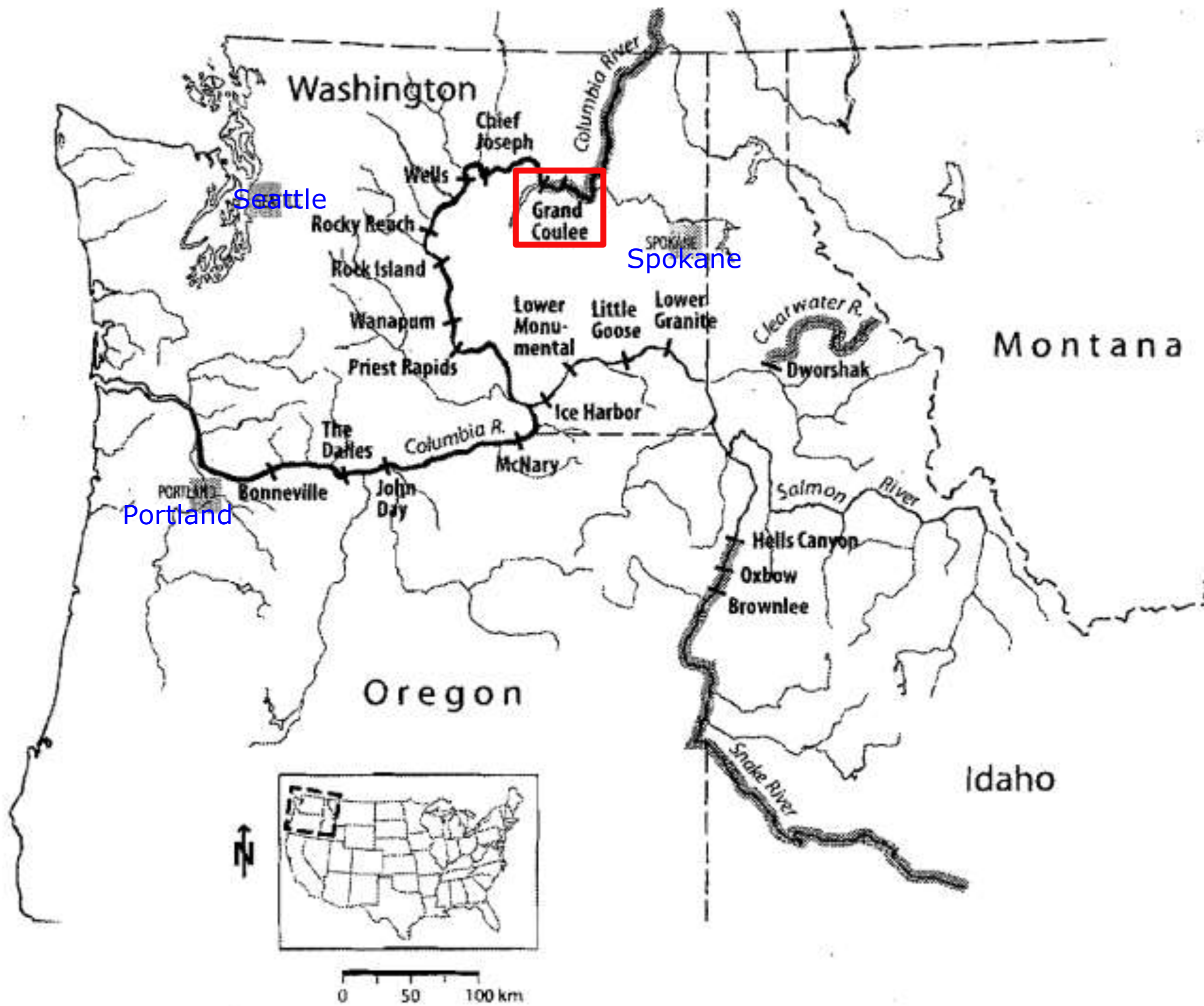
Buttress dam, external structural support braces.



Non-rigid trapezoidal embankment dam, reinforced core.

Columbia River Basin

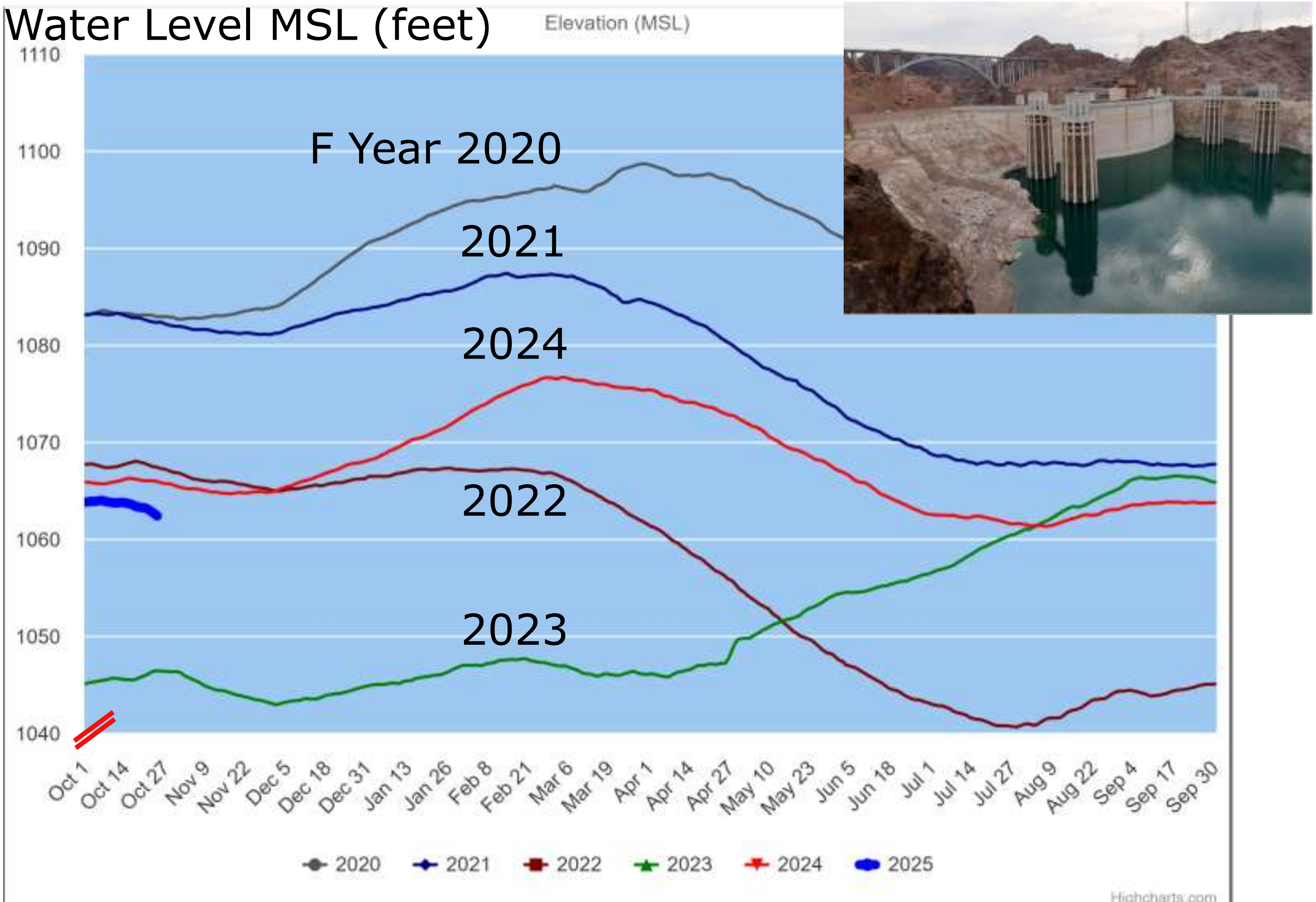
Map showing the Columbia River Basin with its major tributary the Snake River. Large mainstem dams are noted on the lower Snake and Columbia Rivers. Shaded areas indicate historic salmon spawning areas now blocked by dams



Columbia, Colorado and other rivers have multiple dams, hydro-electric power, flood control, and irrigation.

Infringement on local habitat, culture/way of living has been resisted.
Similar public issues in Europe, South America.

Lake Mead Water Level: Recent History



Hoover Dam with Lake Mead Reservoir

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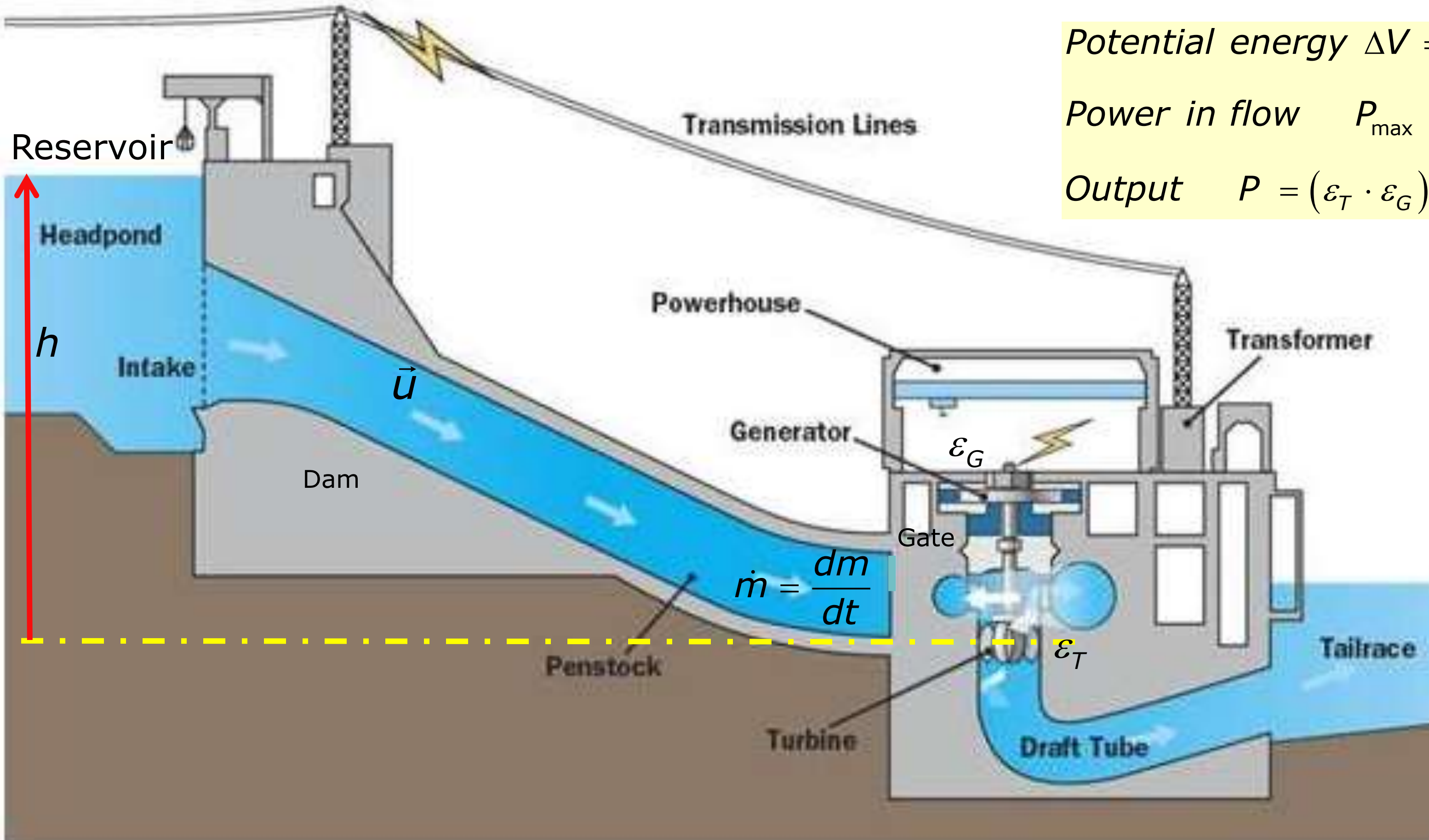
Schematics: Hydro-Electric Power Plant

Conversion gravitational potential → electric power



Potential energy $\Delta V = m \cdot g \cdot h$

Power in flow $P_{max} = \dot{m} \cdot g \cdot h$

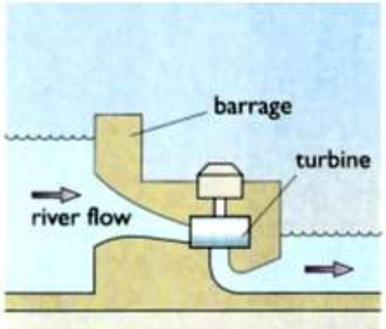
Output $P = (\varepsilon_T \cdot \varepsilon_G) \cdot \dot{m} \cdot g \cdot h$

Dam head h — *Efficiencies* $\varepsilon_T, \varepsilon_G$

Mass of water m — *of turbine, generator*

Flow $\dot{m} = dm/dt$

Types of Hydro-Electric Dams



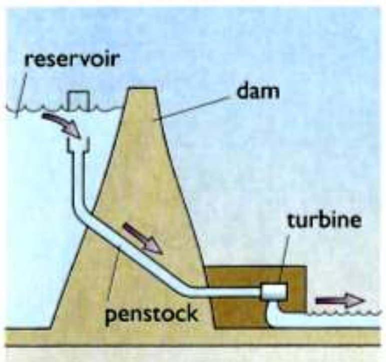
Hydro dams are classified according to head height or construction.

Low-head (10-25 m) dams have low water pressure

→ need large flow volumes (high kinetic energy)

Installed at slow moving rivers, "run-of-the-river"

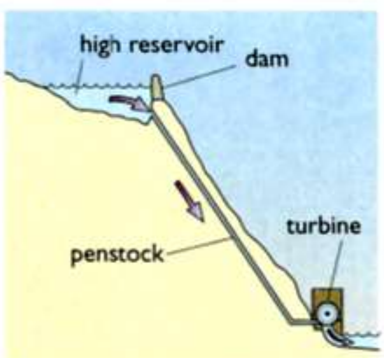
Construction: barrage/embankment type, locks, fish ladders.



Intermediate-head dams have high water pressure

→ need smaller flow volumes.

Installed at river valleys/canyons, fed from very large artificial reservoirs created by flooding extensive areas, reliable power provider, if sufficient precipitation/snow & ice melting occurs.
Construction: arch, gravity, buttress types.



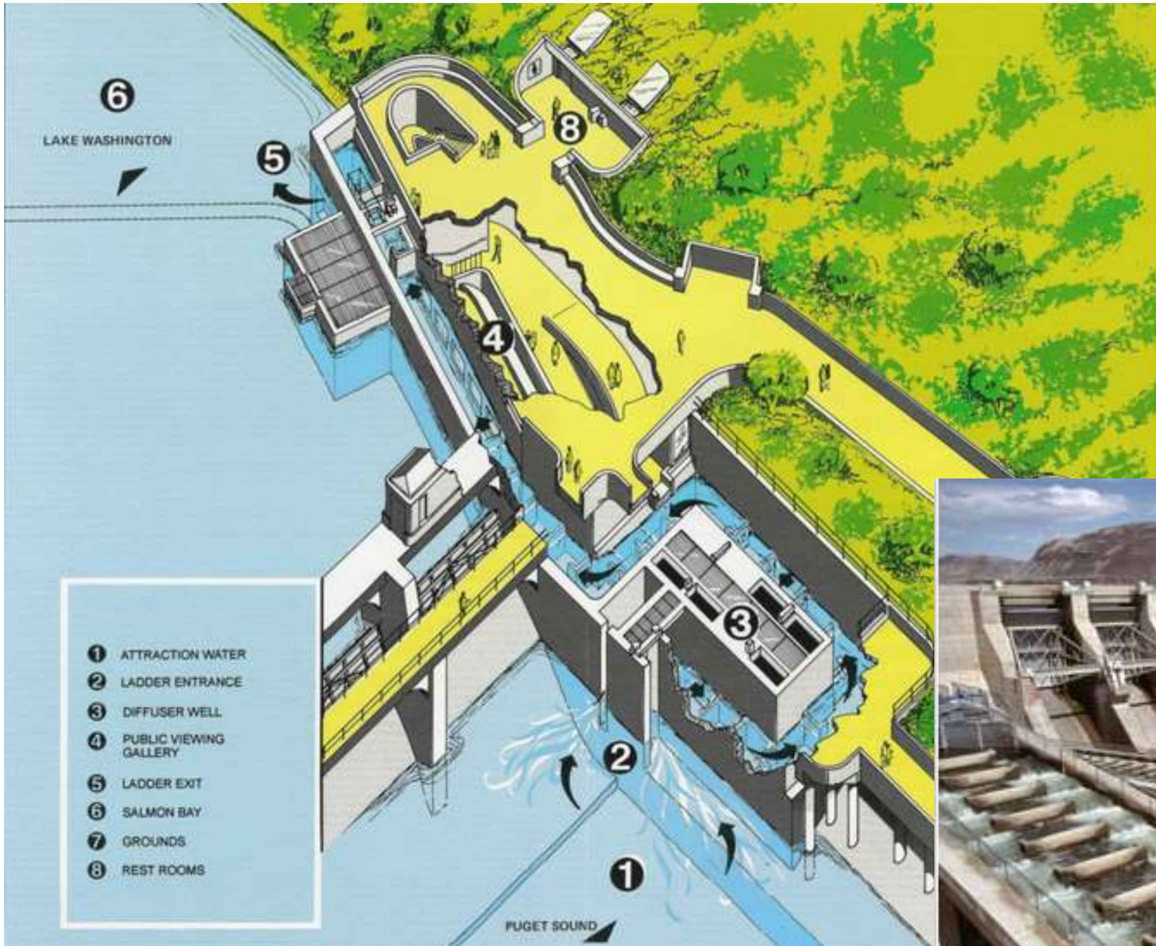
High-head dams have reservoirs located high above power plant,
→ work with small flow volumes but at high water pressures (high potential energy).

Installed in mountainous regions, long penstock tubes,

Construction: gravity/arch types.

G. Boyle, Renewable Energy, OUP 2004

Accommodating Wildlife: Fish By-Pass Ladders

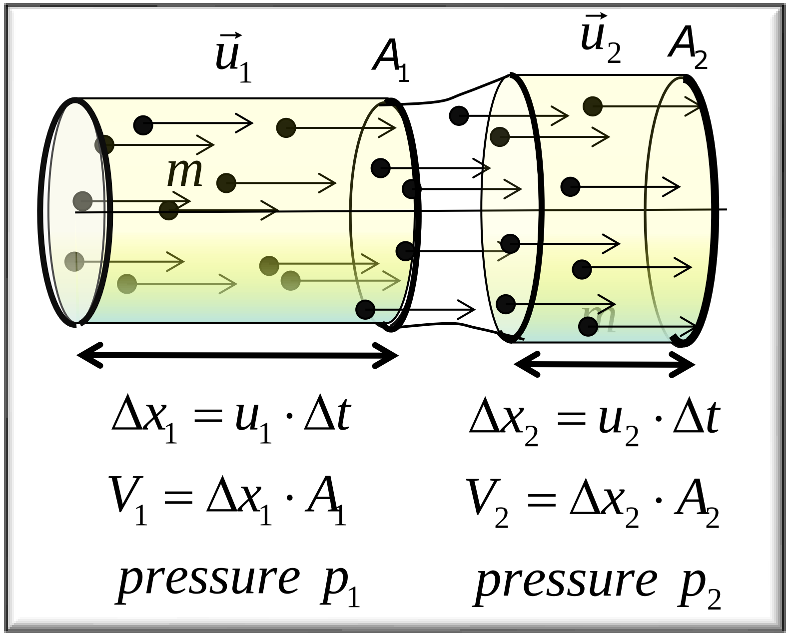


Some low-head dams have installations providing passage for fish to upstream spawning areas or fish hatcheries.
Not available at large dams → effect on habitat/fisheries.

For dams with high head (> 100 m): Fish ladders not practical, or expensive, typical gradients < 20% (1′ elevation per 5′).

Fluid Dynamics
Turbine Technology

Energy Transport: Ideal Fluid Dynamics Laws



Ideal incompressible, non-viscous liquid, "streamlines" (irrotational flow, no inertia)

Number density : $\rho = const.$ $[\# N/cm^3]$

Mass density : $\rho_m = m \cdot \rho = const.$ $[g/cm^3]$

Flux (# particles / time) through area $A = A_\perp$

$$\dot{N} = \frac{\Delta N}{\Delta t} = j \cdot A = \rho \cdot u \cdot A \rightarrow \frac{\Delta m}{\Delta t} = \rho_m \cdot \underbrace{(u \cdot A)}_{dV/dt}$$

Incompressibility ($\rho_1 = \rho_2$)→equal # of particles flow out of V_1 and into V_2.

$$|\dot{N}_1| = j_1 \cdot A_1 = \rho \cdot u_1 \cdot A_1 = \rho \cdot u_2 \cdot A_2 = j_2 \cdot A_2 = |\dot{N}_2|$$

Pushing particles from V_1 to V_2 requires **work**
$\Delta w = -p \cdot \Delta V = \Delta(E_{kin} + U_{pot})$ → **power=**

Force, $\Delta V/\Delta t$

$$\frac{\Delta w_{1\to2}}{\Delta t} = \left[\left(p_2 \cdot A_2\right) \cdot u_2 - \left(p_1 \cdot A_1\right) \cdot u_1\right] = \frac{\Delta m}{\rho_m \Delta t}\left(p_2 - p_1\right)$$

$$Loss(?)\ \Delta E_{kin} = (1/2) \cdot \rho_m \cdot \left(u_2^2 \cdot A_2 - u_1^2 \cdot A_1\right)$$

$$Gain(?)\ \Delta V_{Pot} = \Delta m\left(\upsilon_{Pot,2} - \upsilon_{Pot,1}\right), \quad \Delta m = \rho_m \cdot A \cdot u \cdot \Delta t$$

$$\frac{\Delta m}{\rho_m \Delta t}\left(p_1 - p_2\right) = (1/2)\frac{\Delta m}{\Delta t}\left(u_2^2 - u_1^2\right) + \frac{\Delta m}{\Delta t}\left(\upsilon_{Pot,2} - \upsilon_{Pot,1}\right)$$

Continuity Equation

$$j_m \cdot A = \rho_m \cdot u \cdot A = \frac{\Delta m}{\Delta t} = const.$$

Bernoulli Equation

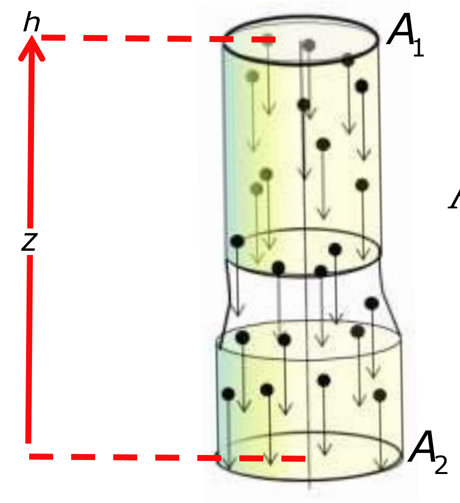
$$p + (1/2)\rho_m u^2 + \rho_m \upsilon_{Pot} = \frac{E}{V} = const.$$

Gravitational Flow Energy Conversion

Apply *Bernoulli Equation* to flow of water with gravitational energy $\Delta V_{pot}=V_{pot}=m\cdot g\cdot h$

At $z=\boldsymbol{h}$: $p=0,\ u=0,\ V_{pot}=m\cdot g\cdot h$

$$\cancel{p} + \frac{1}{2}\rho_m \cancel{u^2} + \rho_m \upsilon_{Pot} = \rho_m \cdot g \cdot h$$



$$A_1 = A_2 = A$$

At bottom, $z=0$: $V_{pot}:=0$
$p \le \rho_m\cdot g\cdot h$ ($=$ for $u=0$)

$$p + \frac{1}{2}\rho_m u^2 + \rho_m \cancel{\upsilon_{Pot}} = \rho_m \cdot g \cdot h$$

Static backup pressure

In free fall through potential difference $\Delta V_{pot}=m\cdot g\cdot h$, no static "backup" pressure differential *(p=0)* → ***"jet"***

$$E_{kin}\ per\ \Delta V \rightarrow (1/2)\rho_m u^2 = \rho_m \cdot g \cdot h \rightarrow \boxed{u = \sqrt{2g\cdot h}}$$

If stream with velocity *u* exits through area A, →
Volume flow rate $\dot{Q} := \dot{V} = dV/dt$ and power $P =$

$$\dot{Q} = \frac{dV}{dt} = A\cdot u = A\cdot\sqrt{2\cdot g\cdot h} \qquad [\,] = Volume/Time$$

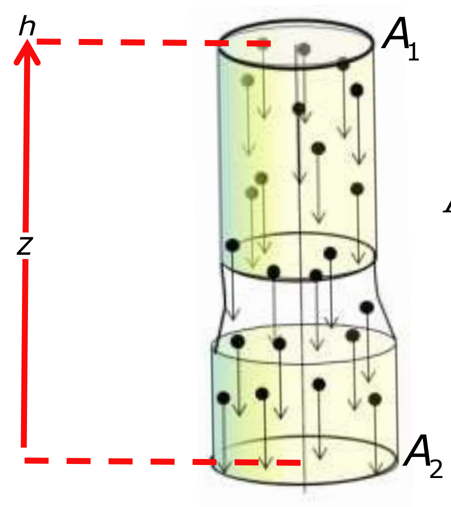
$$P = \underbrace{\dot{Q}\cdot(\rho_m}_{dm/dt}\cdot g\cdot h) \approx 45\cdot A\cdot h^{3/2}\ kW$$

Gravitational Flow Energy Conversion

Apply *Bernoulli Equation* to flow of water with gravitational energy $\Delta V_{pot}=V_{pot}=m\cdot g\cdot h$

At $z=\boldsymbol{h}$: $p=0,\ u=0,\ V_{pot}=m\cdot g\cdot h$

$$\not{p} + \frac{1}{2}\rho_m \not{u}^2 + \rho_m \upsilon_{Pot} = \rho_m \cdot g \cdot h$$



$$A_1 = A_2 = A$$

At bottom, $z=0$: $V_{pot}:=0$
$p \le \rho_m\cdot g\cdot h$ (= for $u=0$)

$$\not{p} + \frac{1}{2}\rho_m u^2 + \rho_m \not{\upsilon}_{Pot} = \rho_m \cdot g \cdot h$$

Static backup pressure, set=0

In free fall through potential difference $\Delta V_{pot}=m\cdot g\cdot h$, no static "backup" pressure differential $(p=0)$ → ***"jet"***

$$E_{kin}\ per\ \Delta V \rightarrow (1/2)\rho_m u^2 = \rho_m \cdot g \cdot h \rightarrow \boxed{u = \sqrt{2g\cdot h}}$$

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$$P = \underbrace{\dot{Q}\cdot(\rho_m}_{dm/dt}\cdot g\cdot h) \approx 45\cdot A\cdot h^{3/2}\ kW$$ Rule of Thumb

Example: Head at $h=175\ m$, diameter of penstock $d=3\ m$ ($A = \pi\cdot(d/2)^2=2.41\text{m}^2$)

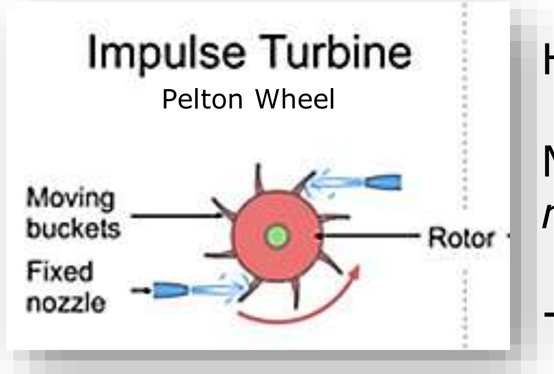
$$u = \sqrt{2\cdot g\cdot h} = \sqrt{2\cdot 9.81\cdot 175}\,\frac{m}{s} = 58.6\,\frac{m}{s}$$

$$\dot{Q} = A\cdot u = 2.41\,m^2\cdot 58.6\,\frac{m}{s} = 141.3\,\frac{m^3}{s} = 1.4\cdot 10^5\ L/s$$

$$\rightarrow \boxed{P = 251\ MW\ (= P_{max})\quad contained\ in\ flow}$$

Power generation in turbines →

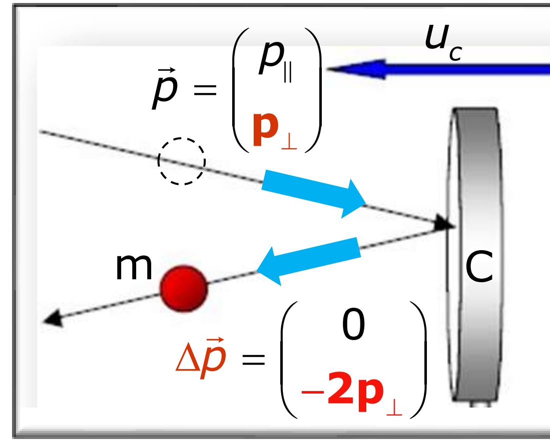
Power Generation in Impulse Turbines



Heads > 300m @ atm. P

Momentum transfer $\Delta p_\perp$ by m colliding with bucket (C),

→ L-transfer $\Delta\vec{L} = \vec{r} \times \Delta\vec{p}_\perp$



$Mass\ (H_2O)\ flow\ density:\ j_m(u) = \rho_m \cdot u \left[\frac{g}{cm^2 \cdot \Delta t}\right]$

$Bucket\ area\ A_c\ is\ hit\ per\ \Delta t\ by\ \ (velocity\ jet\ u, bucket\ u_c)$

$\Delta m \approx j_m(u-u_c)\cdot A_c \cdot \Delta t, \quad rel.momentum\ p = \Delta m \cdot (u-u_c),$

$(u-u_c) = speed\ relative\ to\ bucket$

$initally\ u_c \ll u,\ increases\ in\ time.$

$\rightarrow\ transfer\ |\Delta p| = 2p\ to\ cup\ in\ \Delta t \rightarrow Force\ F = \Delta p/\Delta t$

$\rightarrow\ F = 2p/\Delta t \approx 2\cdot\left[j_m(u-u_c)\cdot A_c\right]\cdot(u-u_c) = 2\rho_m A_c (u-u_c)^2$

Example of dissipative force

$Energy\ (work)\ transfer\ to\ bucket: \Delta E = F\cdot\Delta x = F\cdot u_c \cdot \Delta t$

$Power\ transferred\ to\ bucket: \ P = F\cdot u_c = \left[2\rho_m A_c\right](u-u_c)^2\cdot u_c$

$Speed\ of\ bucket\ increases,\ \underline{maximum\ power}\ transfer\ P_{max} \rightarrow$ $u_c = \frac{1}{3}u$

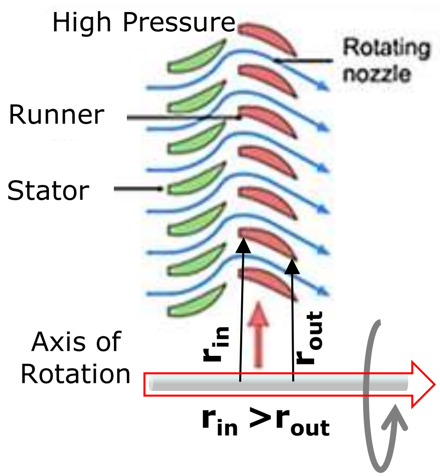
$$P_{max} = \frac{2}{27}\left[\rho_m \cdot A_c\right]\cdot u^3 = \frac{4}{27}\left[\frac{1}{2}\rho_m \cdot u^2\right]\cdot \underbrace{(A_c\cdot u)}_{\dot{Q}=dV/dt} \rightarrow P_{max} = \frac{4}{27}\frac{d}{dt}\left(\frac{m}{2}\cdot u^2\right)$$

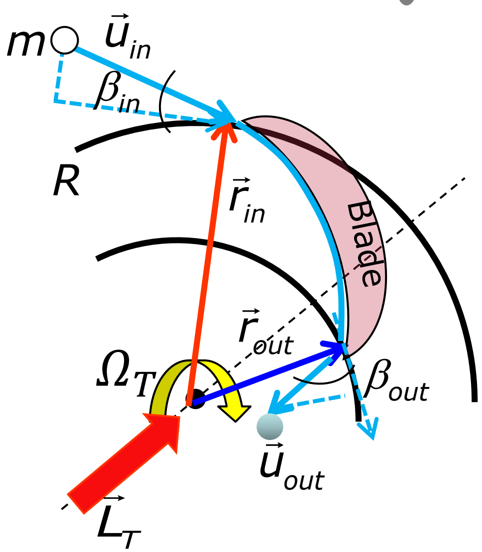
$\varepsilon \lesssim 16\%$

Other Turbines

Angular Momentum Transfer in Reaction Turbines

Gen Reaction Turbine



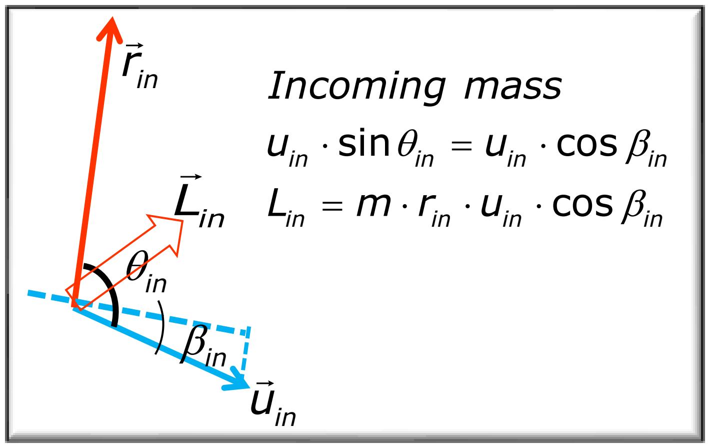


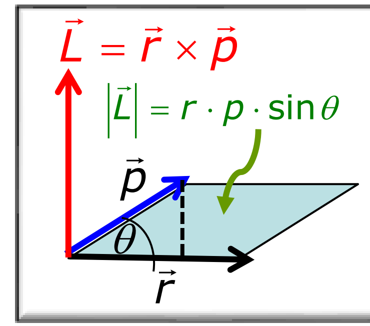
Energy transfer leads to speed up of turbine rotation = increased angular momentum $\vec{L}_T$ by $\Delta\vec{L}_T$.

Fluid has lost this angular momentum.

$$\vec{L}_{out} = \vec{L}_{in} - \Delta\vec{L}_T$$

all parallel





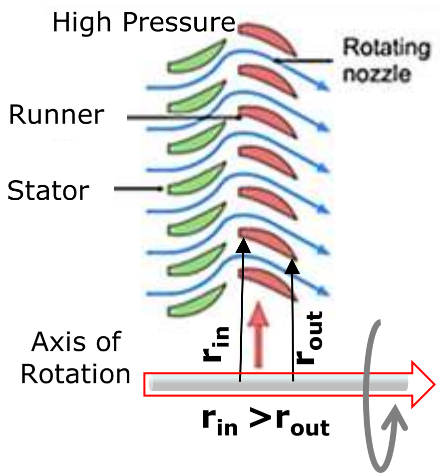
Outer vector product of two vectors $\vec{r}$ and $\vec{p}$

16

Hydro Power

Angular Momentum Transfer in Turbines

Gen Reaction Turbine



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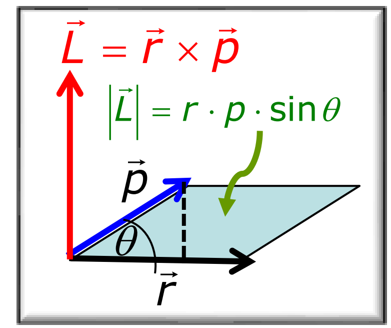

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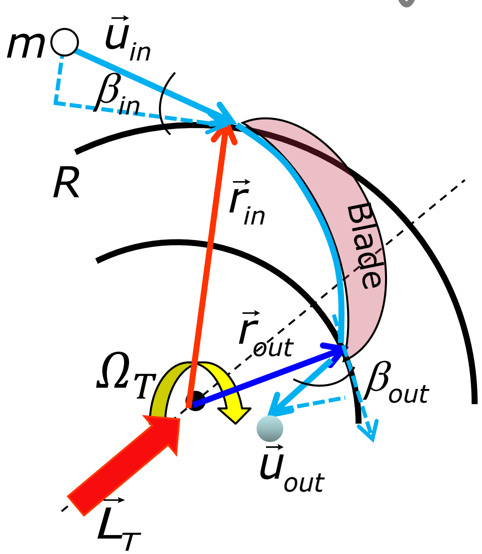
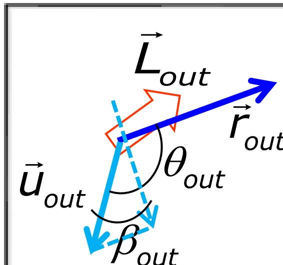




Outgoing mass

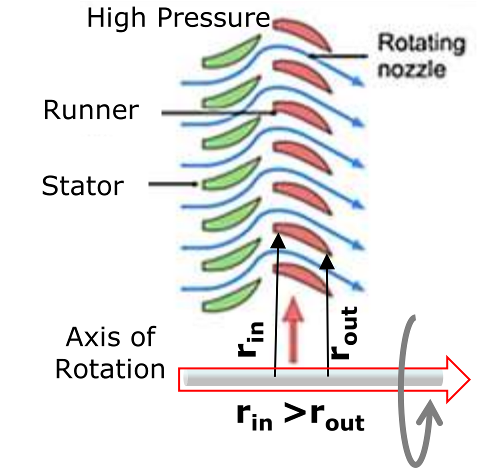
$$u_{out} \cdot \sin\theta_{out} = u_{out} \cdot \cos\beta_{out}$$

$$L_{out} = m \cdot r_{out} \cdot u_{out} \cdot \cos\beta_{out}$$

$$\Delta L_T = L_{in} - L_{out}$$

Angular Momentum Transfer in Hydro Turbines

Gen Reaction Turbine



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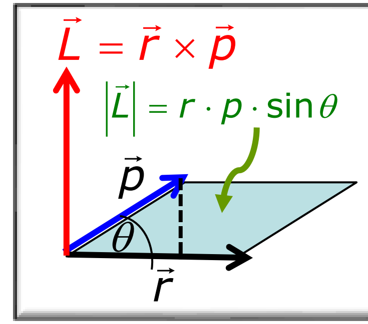
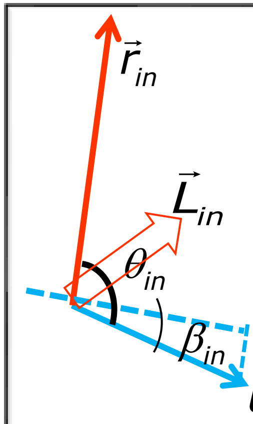


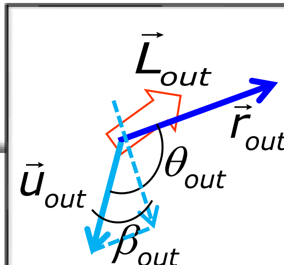
Outer vector product of two vectors $\vec{r}$ and $\vec{p}$



Incoming mass

$$u_{in} \cdot \sin\theta_{in} = u_{in} \cdot \cos\beta_{in}$$

$$L_{in} = r_{in} \cdot \underbrace{(m \cdot u_{in})}_{p_{in}} \cdot \cos\beta_{in}$$

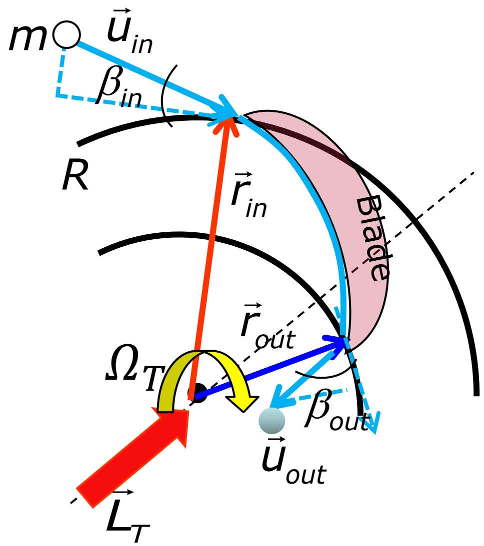


Outgoing mass

$$u_{out} \cdot \sin\theta_{out} = u_{out} \cdot \cos\beta_{out}$$

$$L_{out} = r_{out} \cdot \underbrace{(m \cdot u_{out})}_{p_{out}} \cdot \cos\beta_{out}$$

Transferred : $\Delta L_T = L_{in} - L_{out}$



$\rightarrow$ *Torque* $M = \Delta L_T / \Delta t = \dot{m} \cdot (r_{in} \cdot u_{in} \cdot \cos\beta_{in} - r_{out} \cdot u_{out} \cdot \cos\beta_{out})$

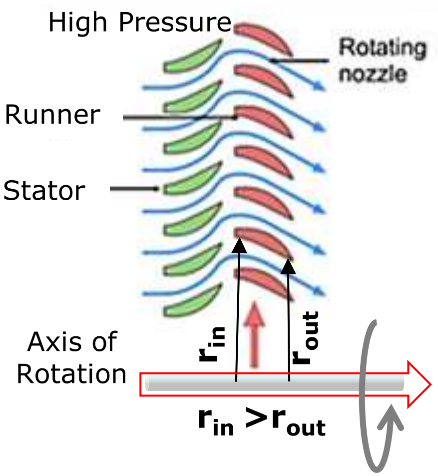
Power $P = M \cdot \Omega_T$; *Mass flow* $\dot{m} = \rho_m \cdot \dot{Q}$

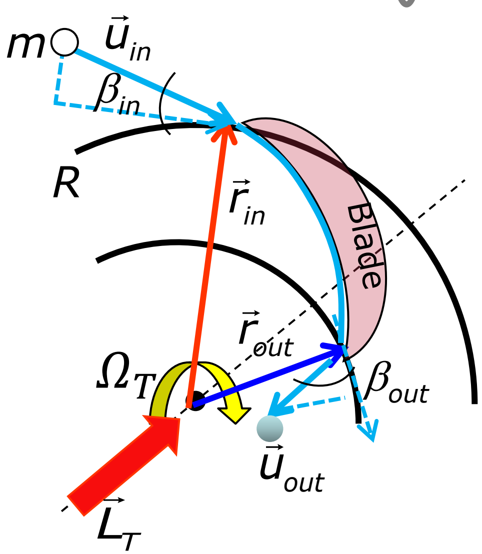
Euler's Turbine Equation

$$P = \Omega_T \cdot \rho_m \cdot \dot{Q} \cdot (r_{in} \cdot u_{in} \cdot \cos\beta_{in} - r_{out} \cdot u_{out} \cdot \cos\beta_{out})$$

Angular Momentum Transfer in Rxn Turbines

Gen Reaction Turbine





Angular momentum to turbine (runner) by driving fluid (water)

$$\Delta\vec{L}_T = \vec{L}_{in} - \vec{L}_{out};\ Torque\ M = \Delta L_T/\Delta t;\ Power\ P = M\cdot\Omega_T$$

Turbine power does not depend on many construction details but blade geometry → maximize angular momentum transfer!

$$P = \Omega_T \cdot \rho_m \cdot \dot{Q}\cdot\left[\left(\vec{r}\times\vec{u}\right)_{in} - \left(\vec{r}\times\vec{u}\right)_{out}\right]$$

Euler's Turbine Equation

Power is maximized if fluid brings in maximum angular momentum ($\beta_{in}=0^0$) and carries no angular momentum on the way out ($\beta_{out}=90^0$) → tangential inflow & radial outflow.

$$P_{max}\left(r_{in}\right) = \Omega_T \cdot \underbrace{\rho_m \cdot \dot{Q}}_{=dm/dt} \cdot r_{in} \cdot u_{in} \cdot \cos\beta_{in} \quad \rightarrow$$

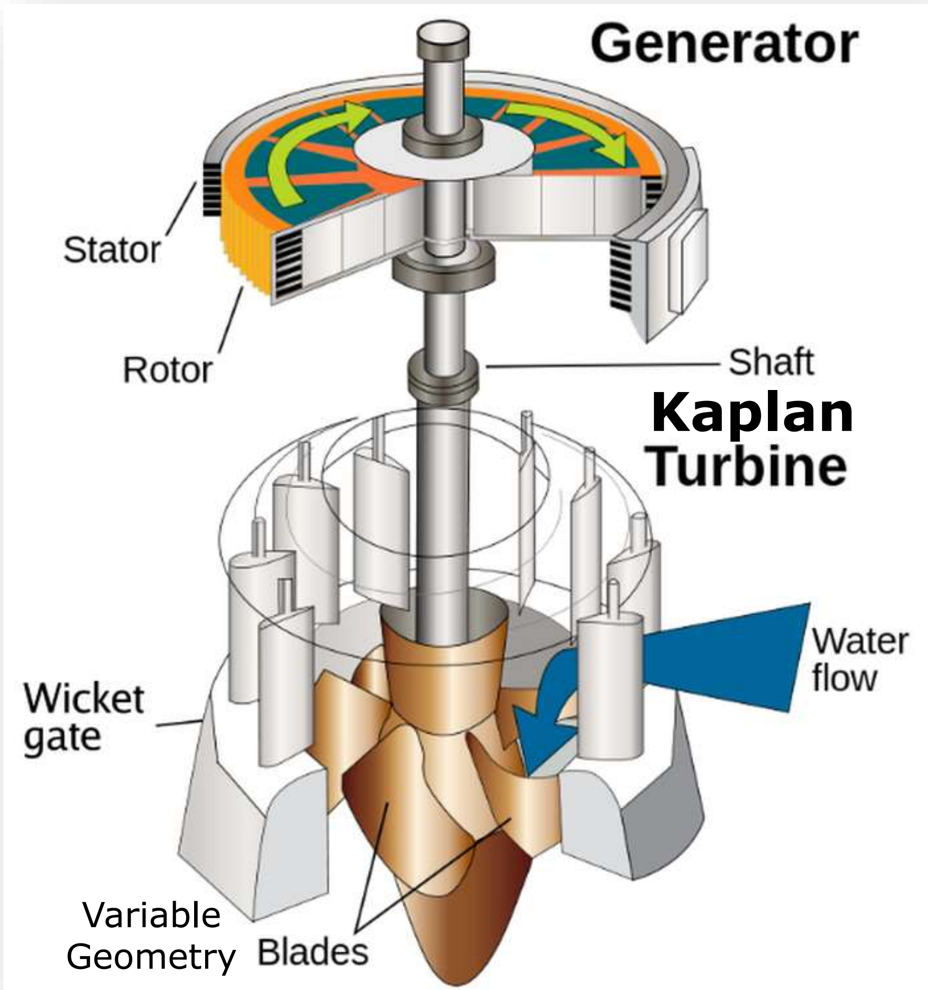
$$P_{max} \le \dot{m}\cdot R\cdot\Omega_T\cdot\left(u_{in}\right)_{tang}$$

R = injection radius for turbine,
$\left(u_{in}\right)_{tang}$ = tangential jet velocity

High power produced by large turbines: high water inflow + tangential injection ($\beta_{in}=0^0$) + radial outflow ($\beta_{out}=90^0$).

Synchronized el. power output steered by governor circuitry controlling gate position.

Turbine Blade Arrangements

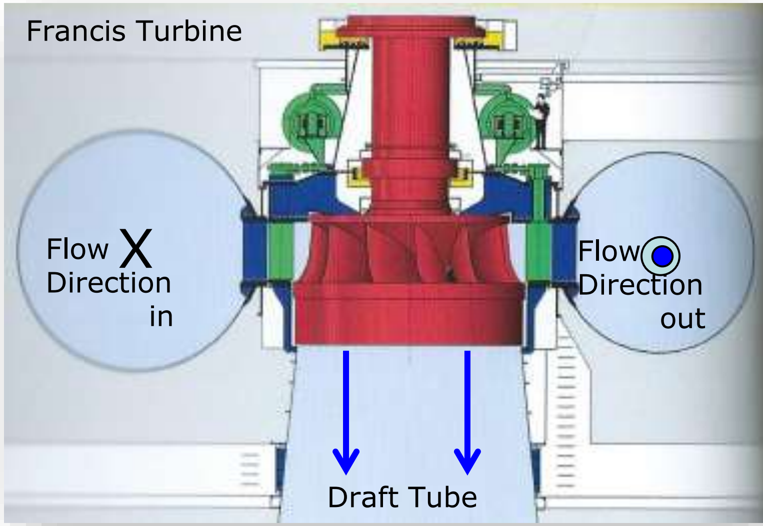


Wikipedia

Propeller turbines for low heads.
Fixed blades or variable pitch.
Schematics of power generation with a Kaplan turbine = high efficiency @all loads.

Francis turbine: Heads< 360 m.
Guide vanes→ tangential injection → radial out flow
"Runner"

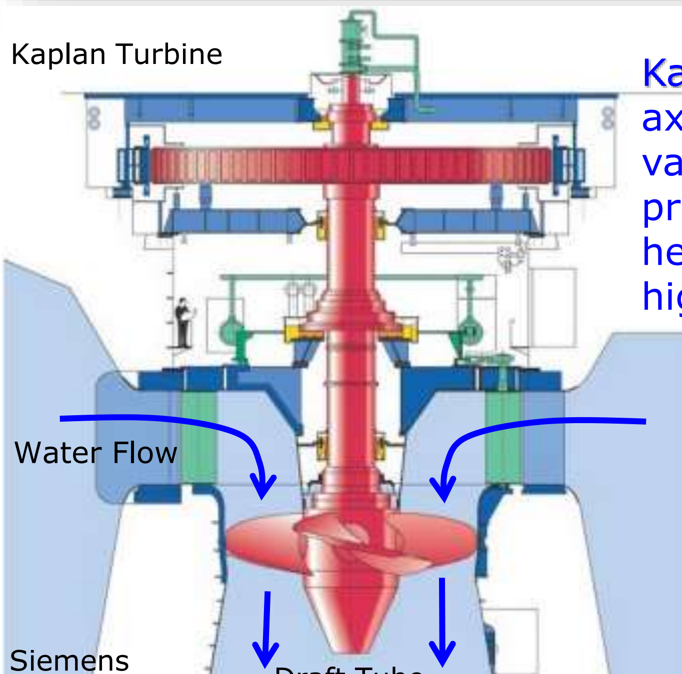
Turbine Types



Hydro turbines are impact or reaction turbines.

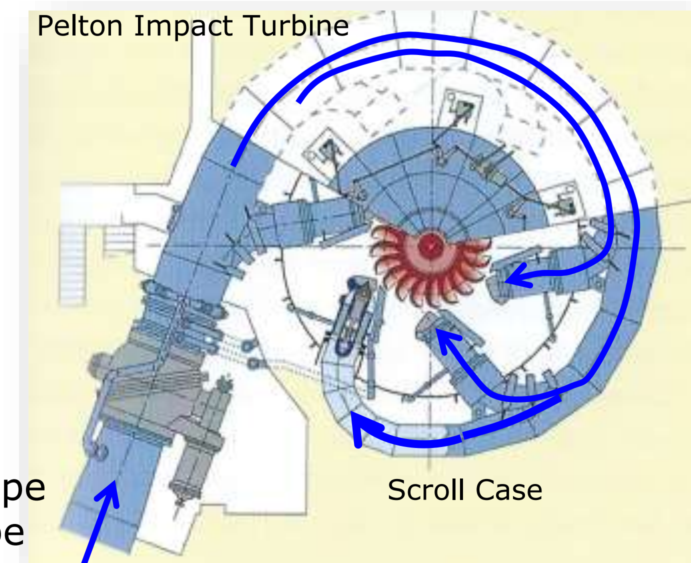
Francis Turbine, radial flow, dia 0.5- 6 m
Fully submerged, horizontal or vertical modes.
Axial outflow.

Popular design, versatile & useful for very different effective heads



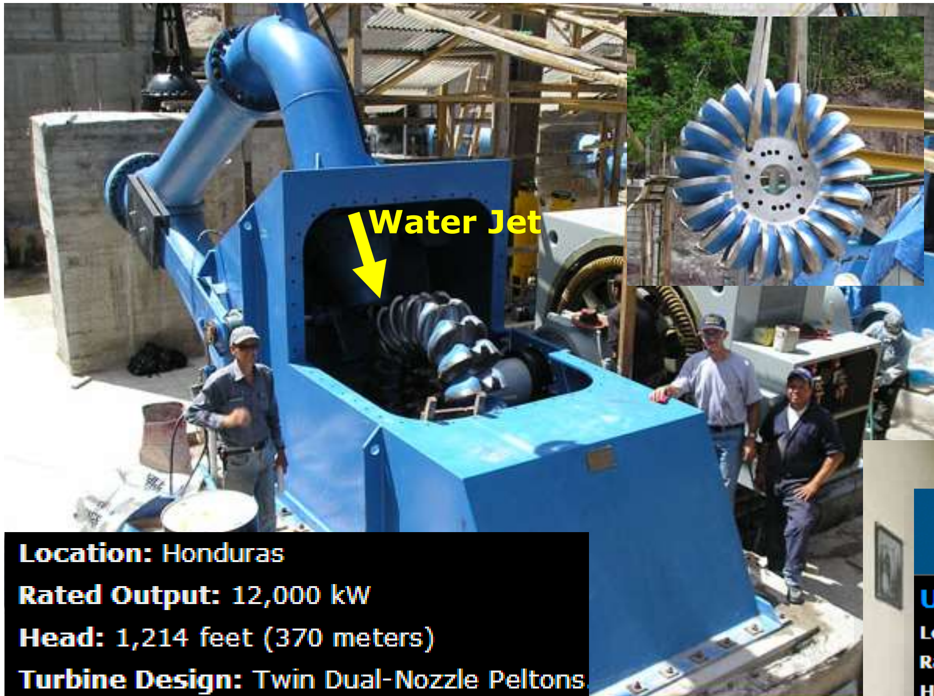
Kaplan Turbine, axial flow, variable-pitch propeller. Low head (<50m), high flow.

Pelton impact/impulse turbine, tangential flow, fixed buckets, low head, low/medium flow.



Scroll type inlet tube

Francis & Pelton Hydro Turbines



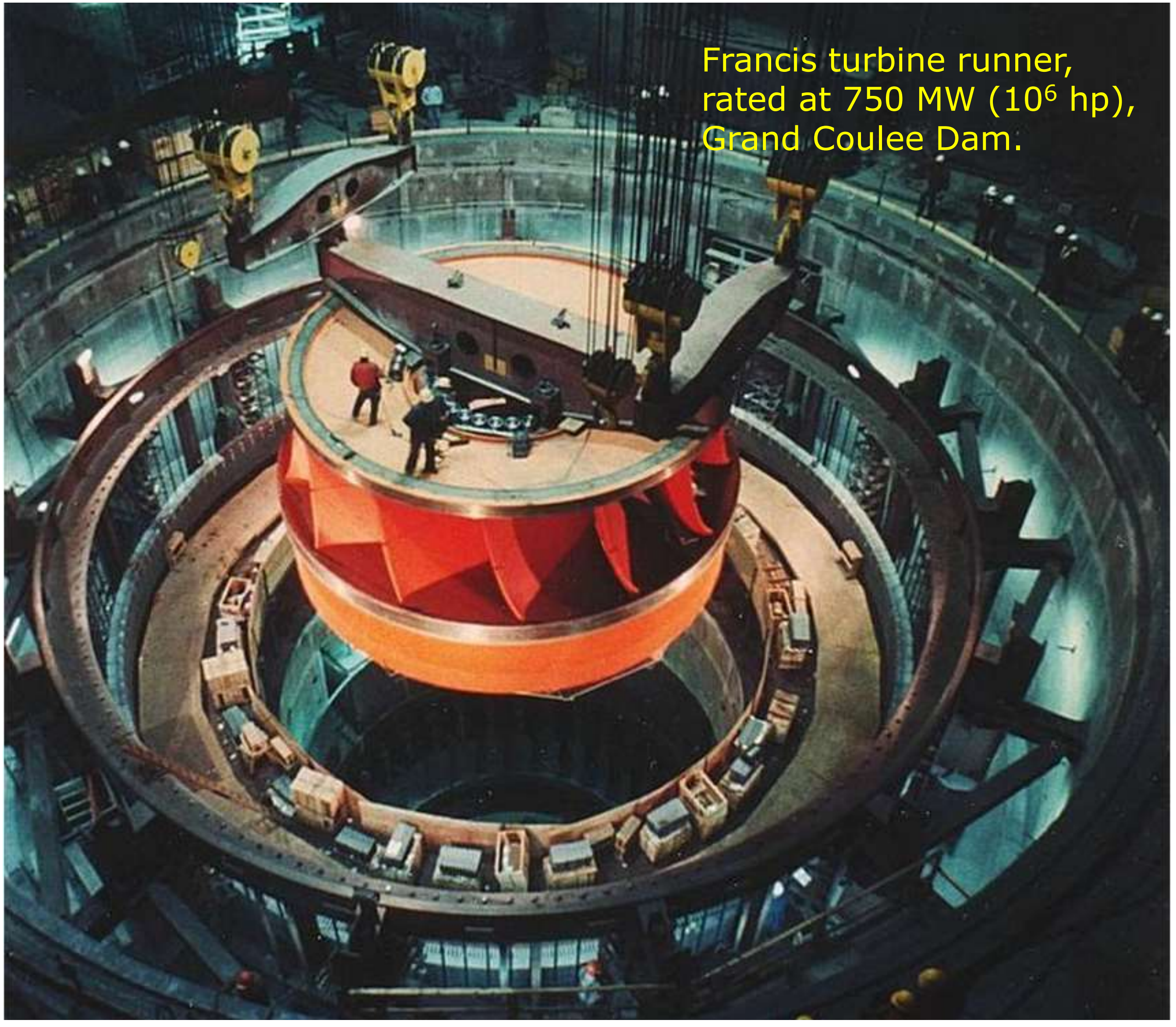
Kaplan & Francis Hydro Turbine Rotors

Public, Wikipedia

A Kaplan turbine after 61 years of service @ Bonneville Dam (313m long, head 23m), Columbia River (US), 8 generators, Total capacity of 558.2 MW.

A Three-Gorges Dam (China) Francis turbine runner before installation.

Grand Coulee Power Plant



Agenda

- Hydroelectric energy resources,
  - Hydrological cycle,
  - Seasonal, climatic trends,
  - Schematics & types of hydroelectric plants,
- Operational principles of hydro power plants,
  - Ideal fluid dynamics laws,
  - Energy & momentum transfer,
  - Hydro turbine types,

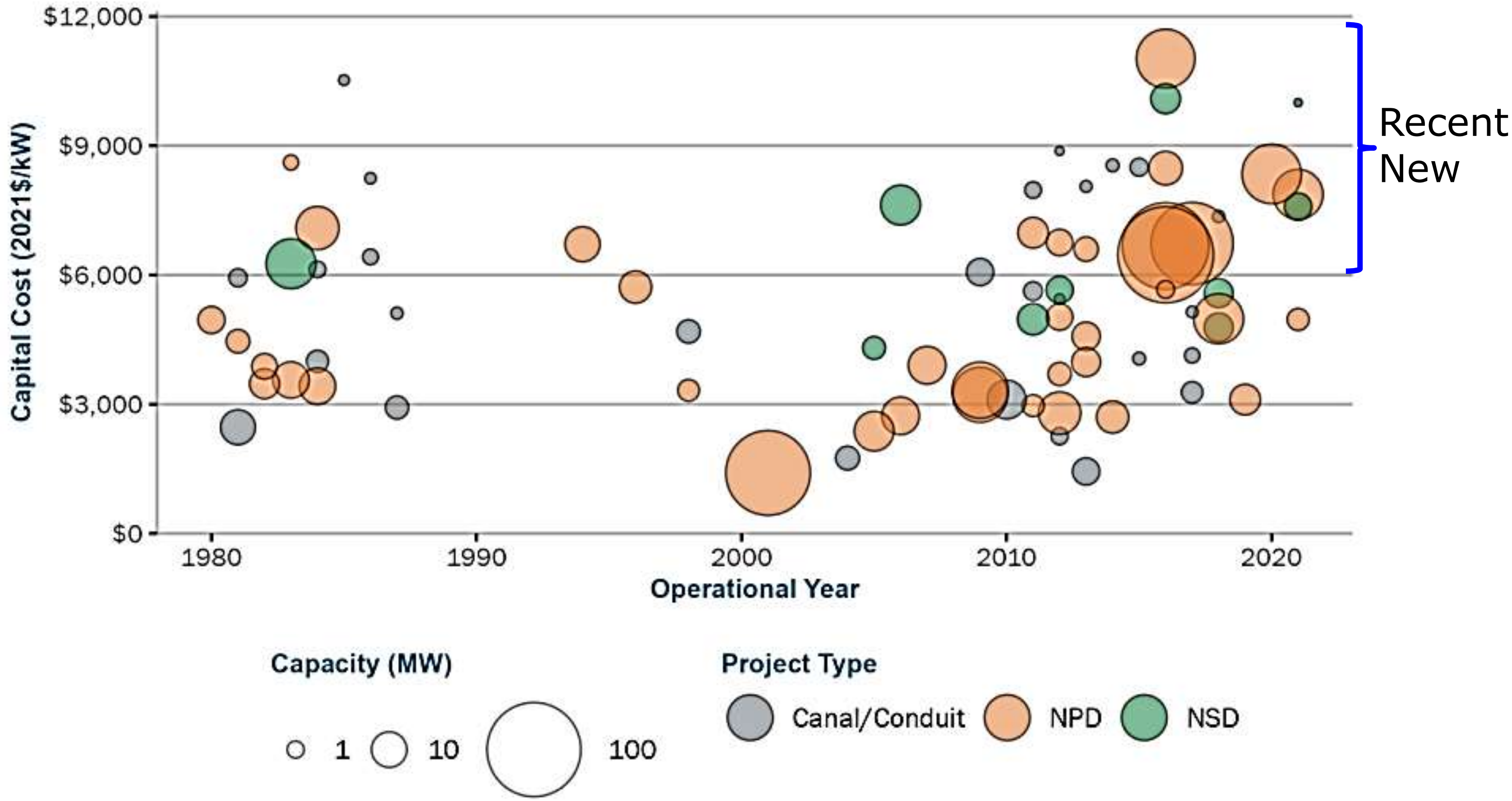
- World/US hydro-electricity generation,
  - Construction cost, electricity price,
  - Consumption,

- Major US and World hydro-electric dam projects,
- Strategic issues of hydro-electric energy production,
  - ecological impact, emissions,
  - non-renewable aspects.

- Next topic: Power from Biomass

Reading Assignments
A&J Ch. 4, 5.1-5.7
LN 3.2

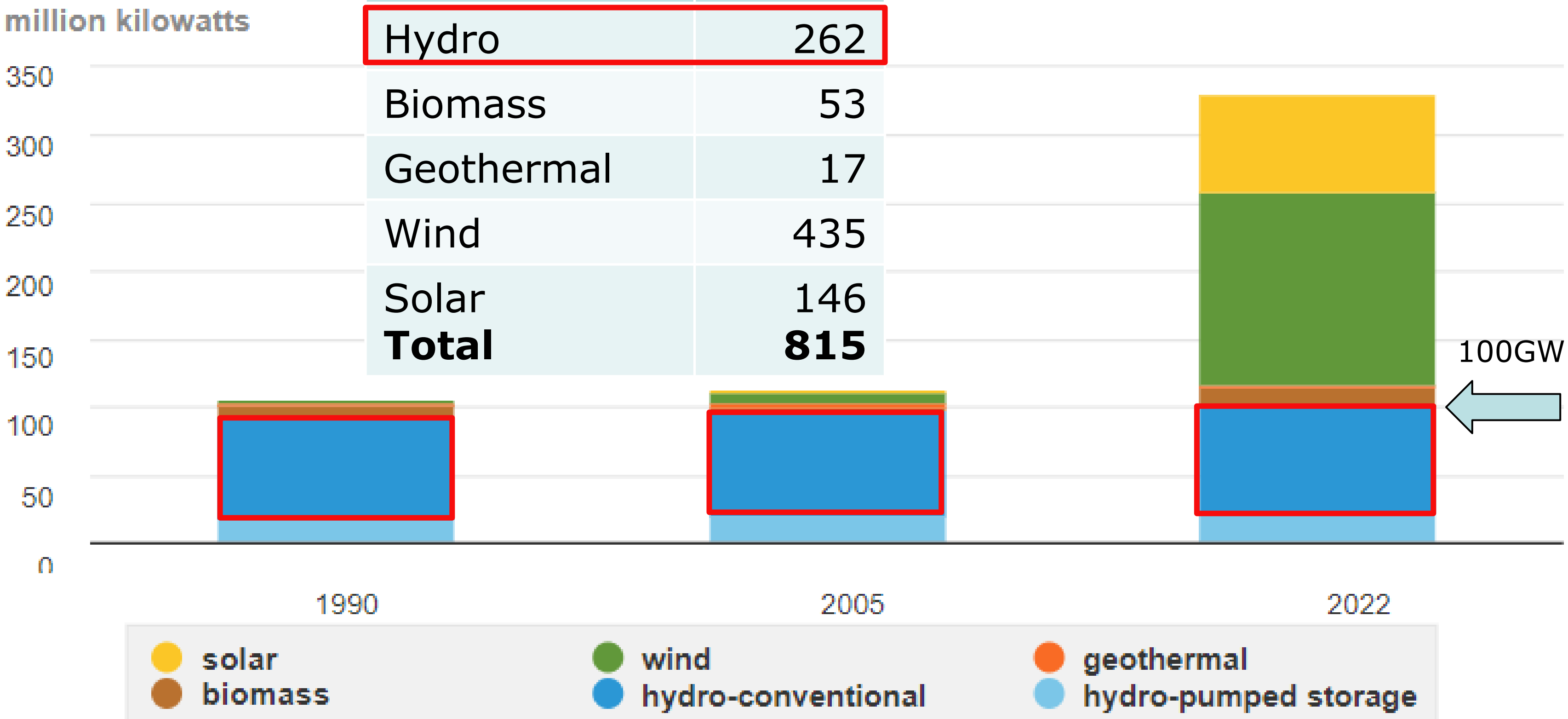
U.S. Capital Cost Of New Hydropower Plants



Sources: O'Connor (2015), IIR, and internet searches
Note: The U.S. Bureau of Reclamation Construction Cost Trends composite trend index was used to adjust for inflation cost data from different years.

US Renewable Electricity Capacity/Generation 2022

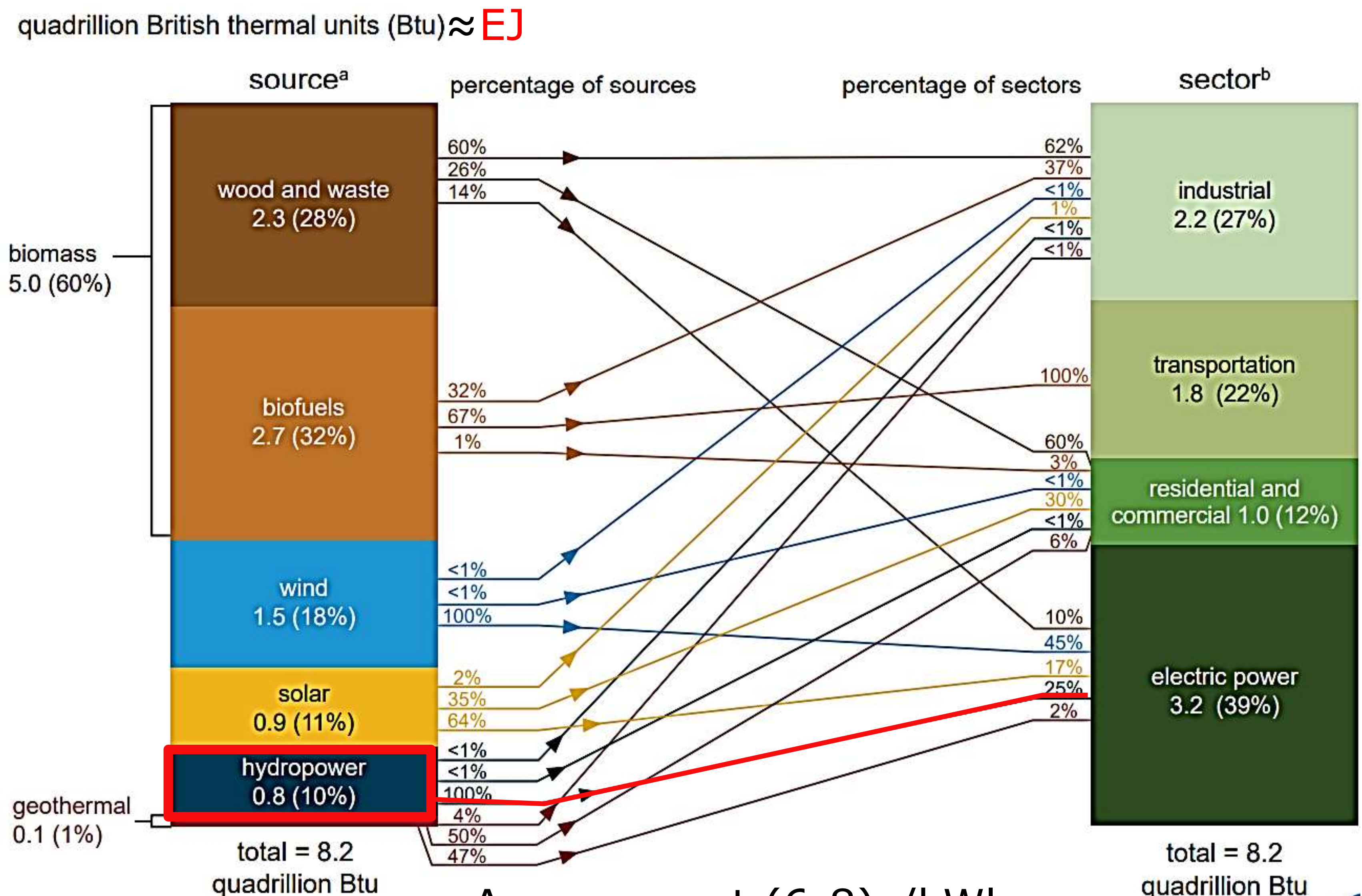
2022 Source	TWh
Hydro	262
Biomass	53
Geothermal	17
Wind	435
Solar	146
Total	**815**



Data source: U.S. Energy Information Administration, *Annual Energy Review 2011* and *Electric Power Monthly*, February 2022, preliminary data for 2021

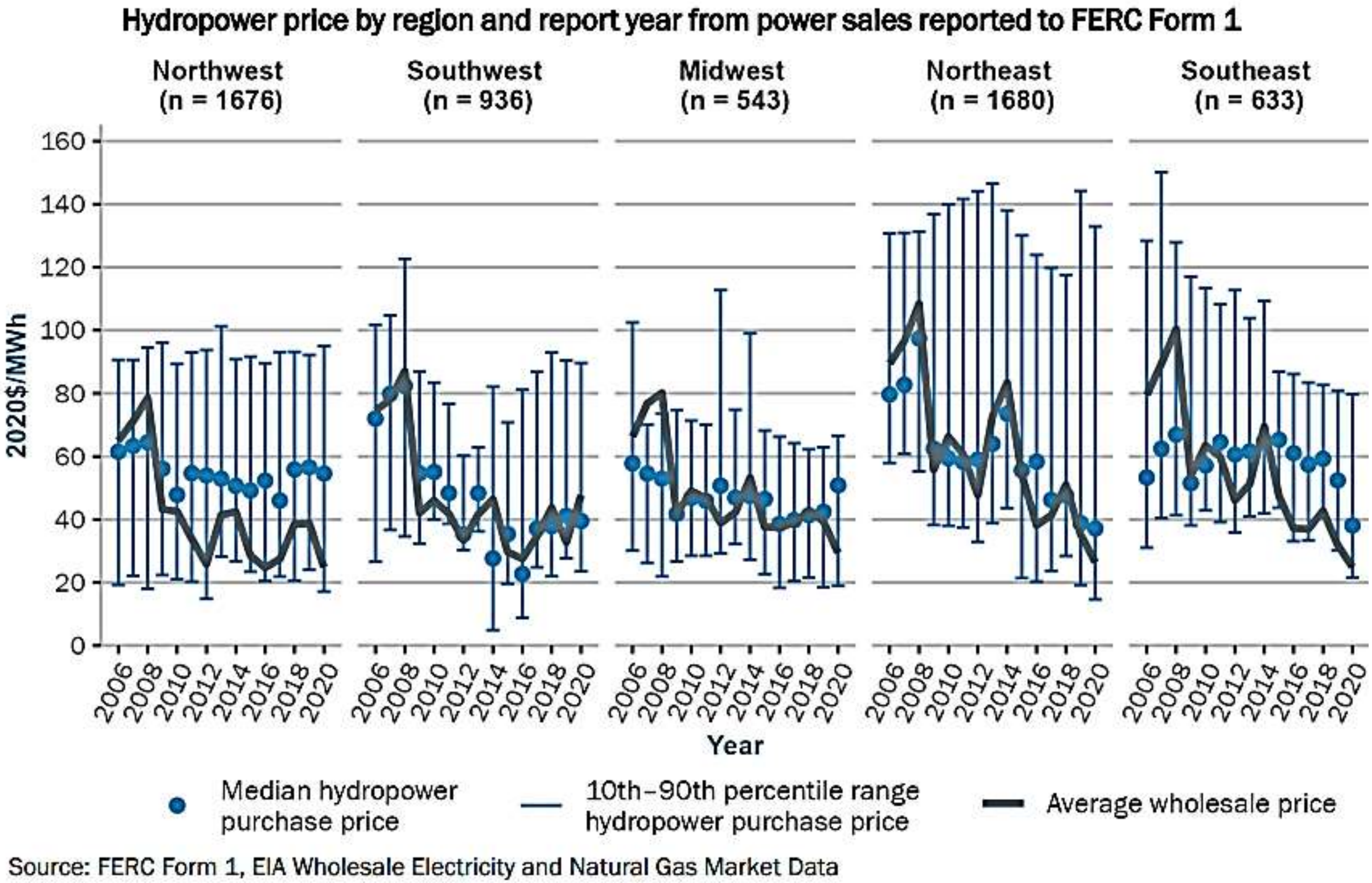
Note: Includes net summer capacity of power plants with at least 1,000 kilowatts of generation capacity. Hydro includes conventional

2023 U.S. 'Renewable' Energy Consumption



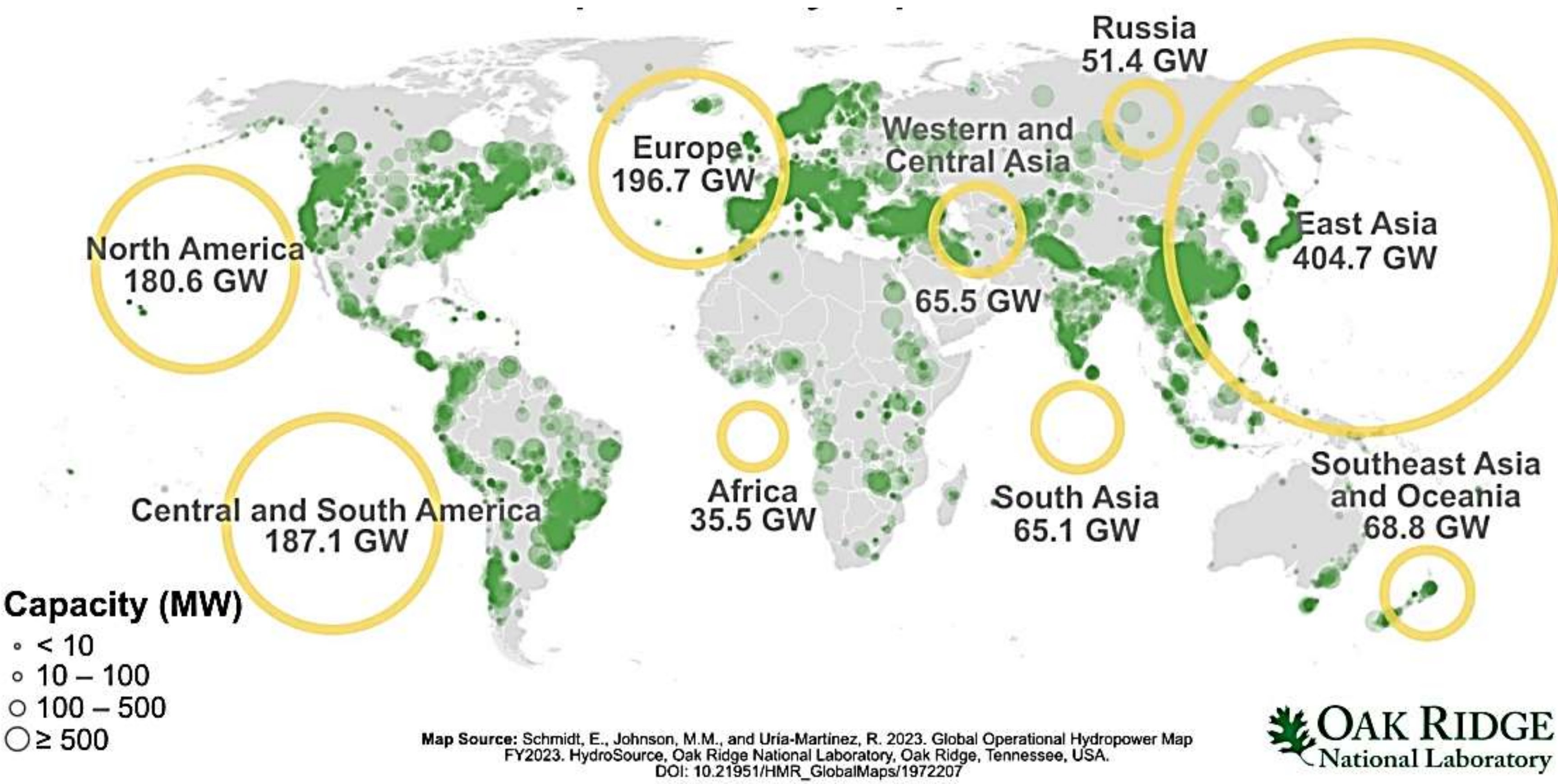
Average cost (6-8)c/kWh

U.S. Hydropower Wholesale Price



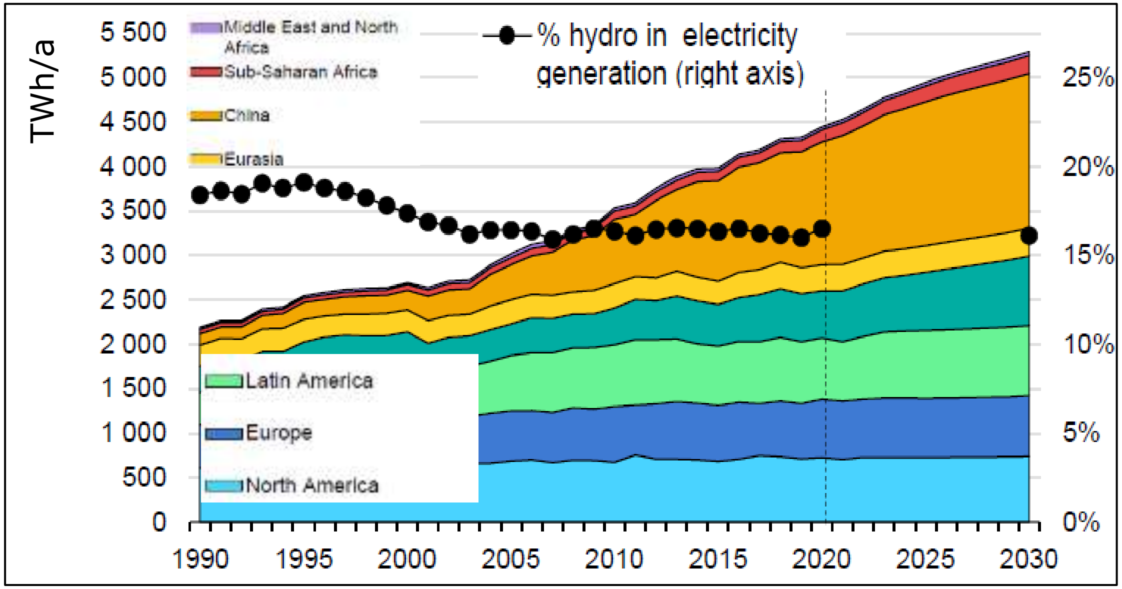
Average cost (6-8)c/kWh

2023 World Operational Hydropower Plants



Sources: Regional totals (IRENA), plant-level data for the United States (ORNL EHA Plant database 2023), plant-level data for rest of world (GlobalData).
Notes: Regional totals include the full capacity from projects that have a mixture of conventional and PSH units.

World Hydro Electricity Production



Long history of hydropower use (mechanical). Now only hydro-electric applications → $\lesssim 16\%$ of total electricity.

Recent increases (x 3) production mainly in China, South America.
Low growth potential in OECD countries, used most resources, issues.

World Commission on Dams (**WCD**) (2000): Most large hydro-electric power plants emit GHG during construction & operation, amounts are "comparable to fossil fuel plants of same capacity."

Submerged organic matter decays anaerobically, producing CH_4 (instead of CO_2)→ not actually "green & renewable"/sustainable.

Direct environmental impact: human & animal habitat, wetlands, river deltas, farm irrigation, fisheries. Catastrophic accidents (Ŧ Ŧ)

Three-Gorges Dam (Yang-Tse)

18 GW **Power generation:** 26 turbines on left and right sides of dam. 2010: +6 underground turbines

Type: Concrete Gravity Dam
Cost: Official cost US$ 25 B (actual cost believed to be higher)
Construction: 1993 - 2009
Reservoir: 660km long, 632 km^2.
Head: 175 m.

Environmental Impact:
Positive flood control.
Submerged ~100 villages, displaced > 1 M persons.

Navigation: Two-way lock system became operational in 2004. One-step ship elevator.

Photo taken on July 4, 2012 shows the interior scene of the Three Gorges' underground power station in Yichang, Central China's Hubei province. [Photo/Asianewsphoto]

Hydropower Strategic Issues

1. Requires specific geographic topology (mountains, deep valleys)
2. Requires flooding of large surface area, arable soil destruction
3. Displacement of human settlements, culture, loss of animal habitat
4. Requires large amounts of water in reservoir & operation (rivers, precipitation)
5. Large physical plant, requires large amounts of cement, GHG emissions
6. Seasonal dependence of efficiency (melting snow and ice vs. annual dry periods)
7. Continuous evaporation of water, GHG from reservoir
8. Competes with agricultural, commercial, and residential demand of water
9. Impedes shipping and travel on rivers
10. Poor fatal accident record

External Global Warming Effect of Hydro Dams

Example: 1.3 GW Glen Canyon Dam, Reservoir 653 km², 300-km long “Lake Powell.”
Continuous emission of CH_4 from decay of submerged biomass contributes 70-80% of GWE emitted, TH=20a is not included in GWP below.

$$\text{Global warming effect } (MT = \text{metric ton } CO_2 \text{ equivalent}) \quad GWE := \sum_j M_j \cdot GWP_j$$

$$\text{with } M_j = \text{amount of } GHG_j,\ GWP_j = \text{global warming potential for time horizon } (TH = 20 \text{ years})$$

Major Construction Inputs and GWE (after 20 yr) for Glen Canyon Hydroelectric Plant[a] **1.3 GW installed, *CF*=0.51**

inputs	total MT	unit cost (1992 $/MT)	total cost (1992 $)	GHG emissions (MT of CO_2 equiv) CO_2	+ CH_4	+ N_2O	= GWE
concrete	9 906 809	30[b]	297 652 257	400 792	751	7 898	409 441
excavation (m³)	4 711 405	na	114 839 000	3 812			3 812
turbines and turbine generator sets	na	na	65 193 084	41 725	45	249	42 019
power distribution and transformers	na	na	13 754 764	12 358	16	79	12 453
steel	32 183	385[c]	12 402 138	43 710	29	244	47 583
copper	90	2 368[c]	214 167	186	0	2	188
aluminum	67	1 268[c]	84 804	157	0	2	159
total			503 240 216	500 000	1 000	9 000	500 000

[a] Total emissions are rounded to one significant digit. MT, metric ton; GWE, global warming effect; na, not available. [b] Ref *39*. [c] Ref *40*.

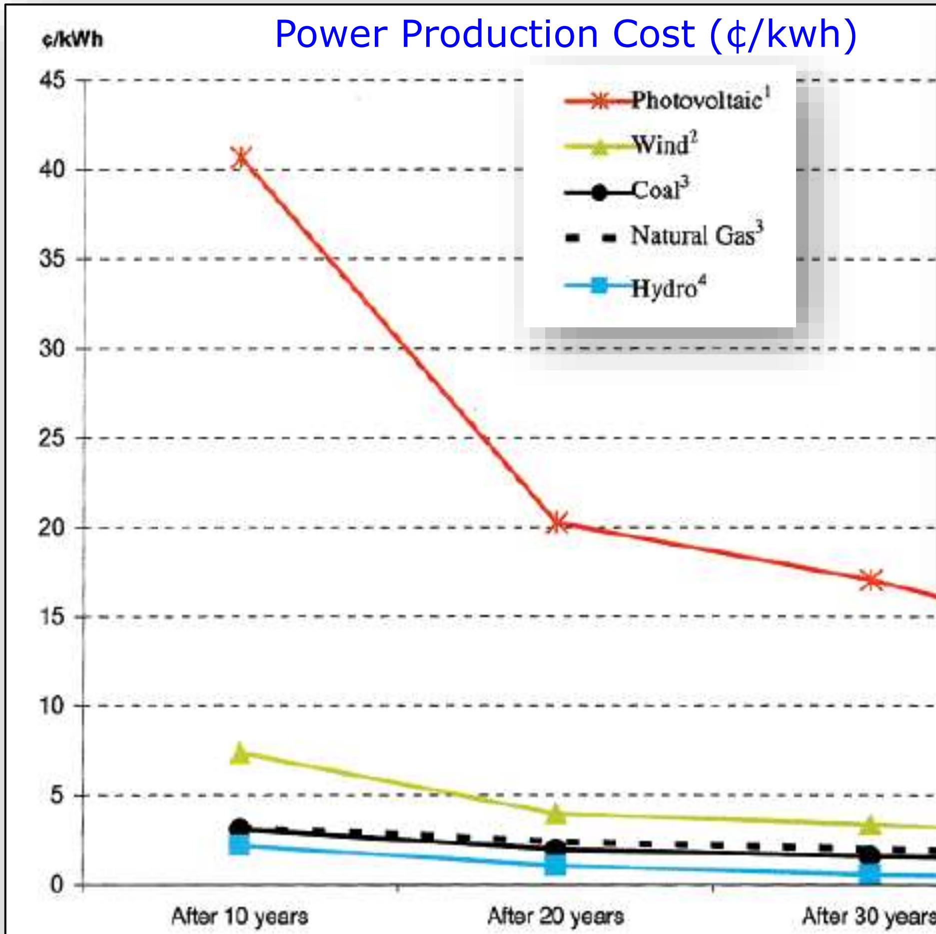
Cost of only construction materials. Includes no labor, installation or maintenance costs.

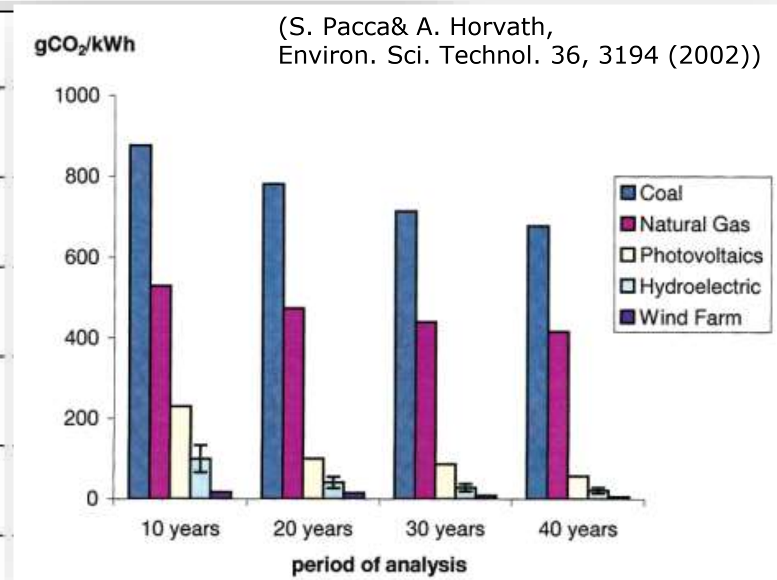
S. Pacca & A. Horvath, Environ. Sci. Technol 36, 3194 (2002)

Pro/Con: Avoided GHG Emissions @ Cost

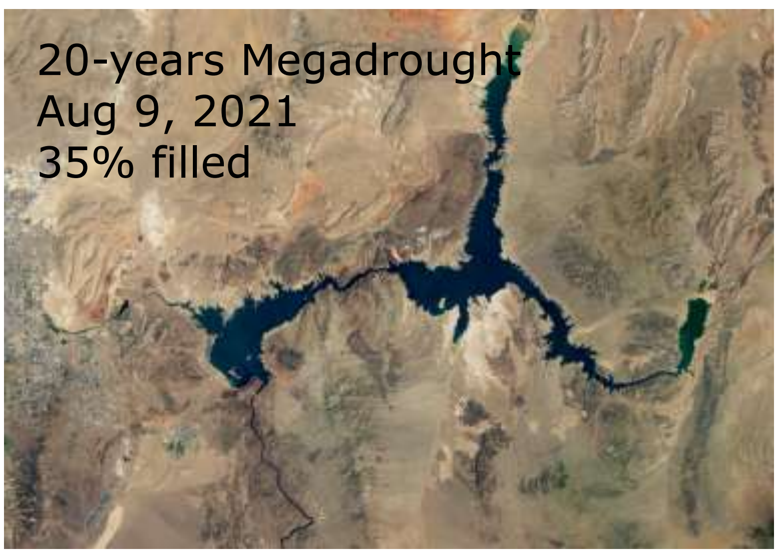
Hydro-electric power has one of the lowest estimated GHG emissions/kWh of all contemporary energy technologies. But continuous CH_4 emission from reservoir is not included.

Estimated CO_2 equivalent needed for construction of infrastructure for a 1.3 GW wind farm is $0.5 \cdot 10^6$ t CO_2. GHG emission is (50g/kWh) 3x higher than for wind farms.

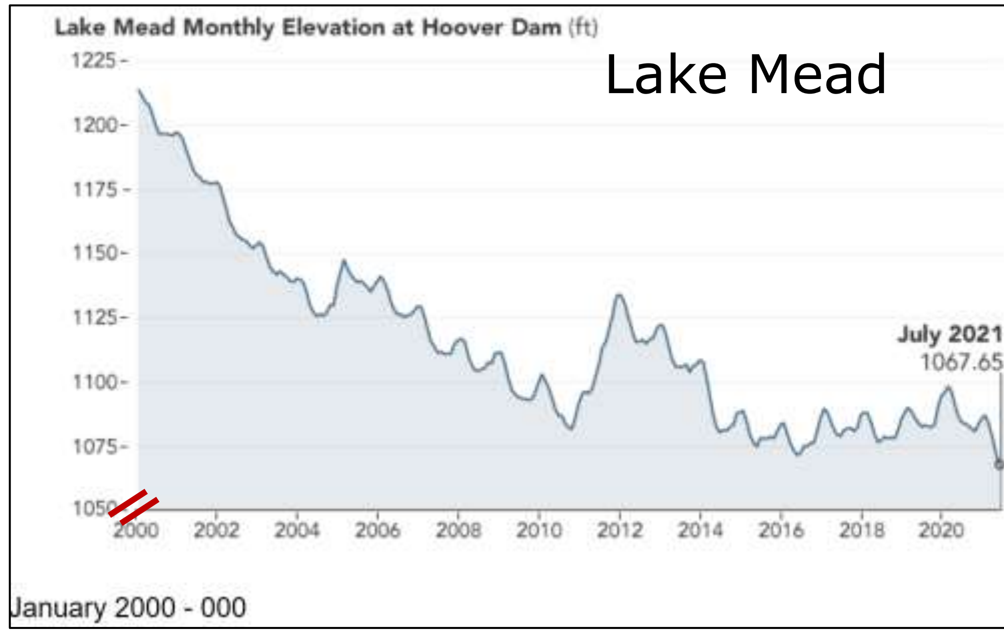




Variation in Colorado River Flow @ Hoover Dam



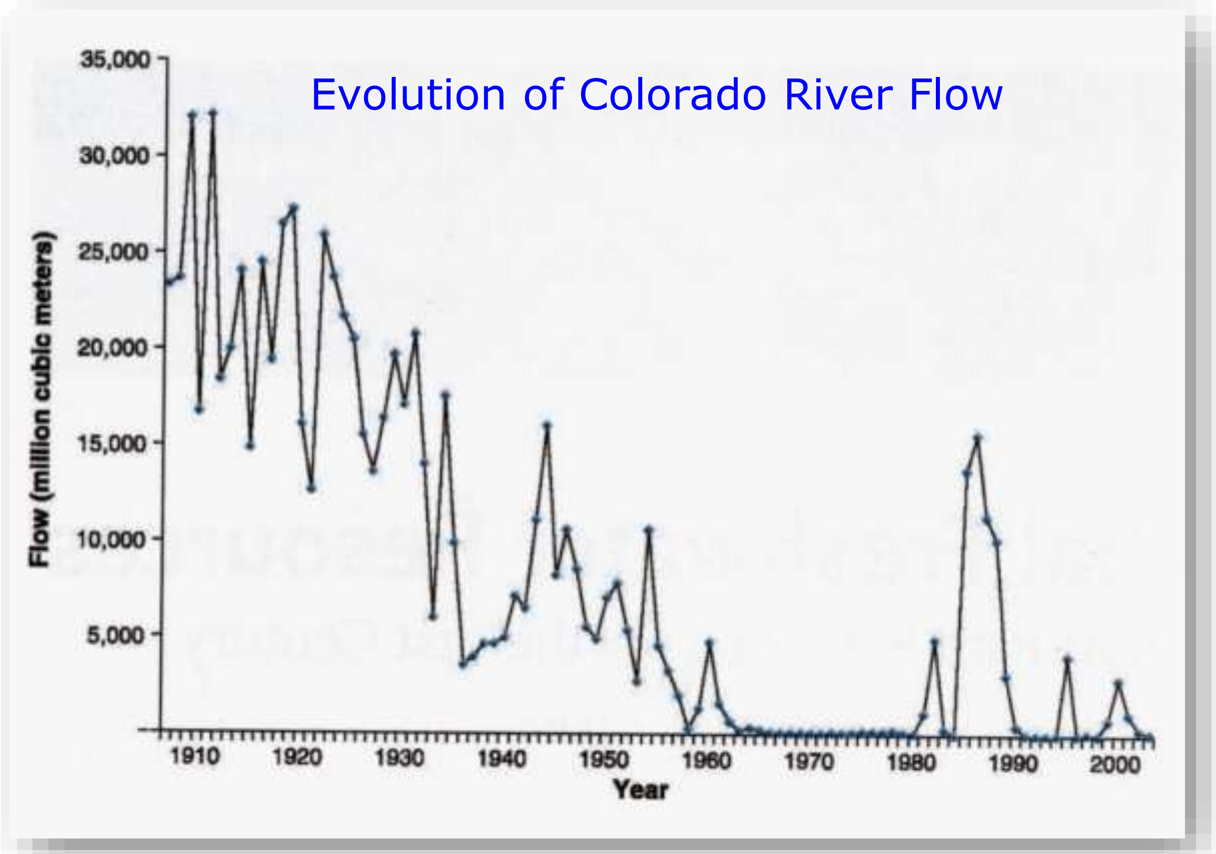
10% of water content supplied locally by precipitation, 90% from annual snow melt of Rocky Mountains.



Pro/Con: Eco-Impact of Hydro Power Dams

Economic and environmental problems:
Season/weather dependence (droughts, winter snow falls, etc.), water supply to farming
Land slides, wetlands, river delta, GHG emissions (World Council on Dams, Report 2000)

Grand Coulee (1942): Villages submerged, Indian culture, economy.
TGD (2007): Villages flooded, (1.5 – 3) M people dislocated.



Examples:
Dammed Colorado river

Amu/Syr Darja (Aral Lake ††)

New Eastern Europe projects.

Very limited growth opportunities for new hydro-power in the developed world.

Hydroelectric Dams: Accidents in Perspective

Summary of accidents with more than five fatalities*

(1970-2008)

Energy chain	OECD		EU27		Non-OECD	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	87	2 259	45	989	2 394[a] 162 818 1 214	38 672 5 788 11 302 15 750
Oil	187	3 495	65	1 243	358	19 516
Natural gas	109	1 258	37	367	78	1 556
Liquefied petro-leum gas	58	1 856	22	571	70	2 789
Hydroelectric	1	14	1	116	9[b] 12	3 961 26 108
Nuclear[c]	–	–	–	–	1	31
Biofuel	–	–	–	–	–	-
Biogas	–	–	–	–	2	18
Geothermal	–	–	–	–	1	21
Wind[d]	54	60	24	24	6	6

* From the Energy-related Severe Accident Database (ENSAD); a) Coal: first line non-OECD total; second line non-OECD without China; third line China 1994-1999; fourth line China 2000-2008; b) Hydro: first line non-OECD without China; second line China; c) Note: Fatalities from the Fukushima Daiichi NPP accident in 2011 are not included in this table, but it should be noted that the accident resulted in no immediate, radiation-related fatalities; d) Wind: only small accidents.

Source: Adapted from Burgherr and Hirschberg, 2014.

→ North-African (Libya) agricultural hydro accident fatalities not included.

Employment in Renewable Energy Sector

Local jobs in the O&M of various electricity generating technologies, ordered by average size of the electricity generating facility

Technology	Jobs/MW	Average size (MW)	Direct local jobs
Nuclear	0.50	1 000	504
Coal	0.19	1 000	187
Hydro > 500 MW	0.11	1 375	156
Hydro pumped storage	0.10	890	85
Hydro > 20 MW	0.19	450	86
Concentrating solar power	0.47	100	47
Gas combined-cycle (CCGT)	0.05	630	34
Photovoltaic (PV)	1.06	10	11
Micro hydro < 20 MW	0.45	10	5
Wind	0.05	75	4

Source: Harker and Hirschboeck, 2010.

Most local employment is during installation 200MW ➔ 500 workers

Many energy sector jobs are not co-local (engineering, design, financing, transient maintenance).

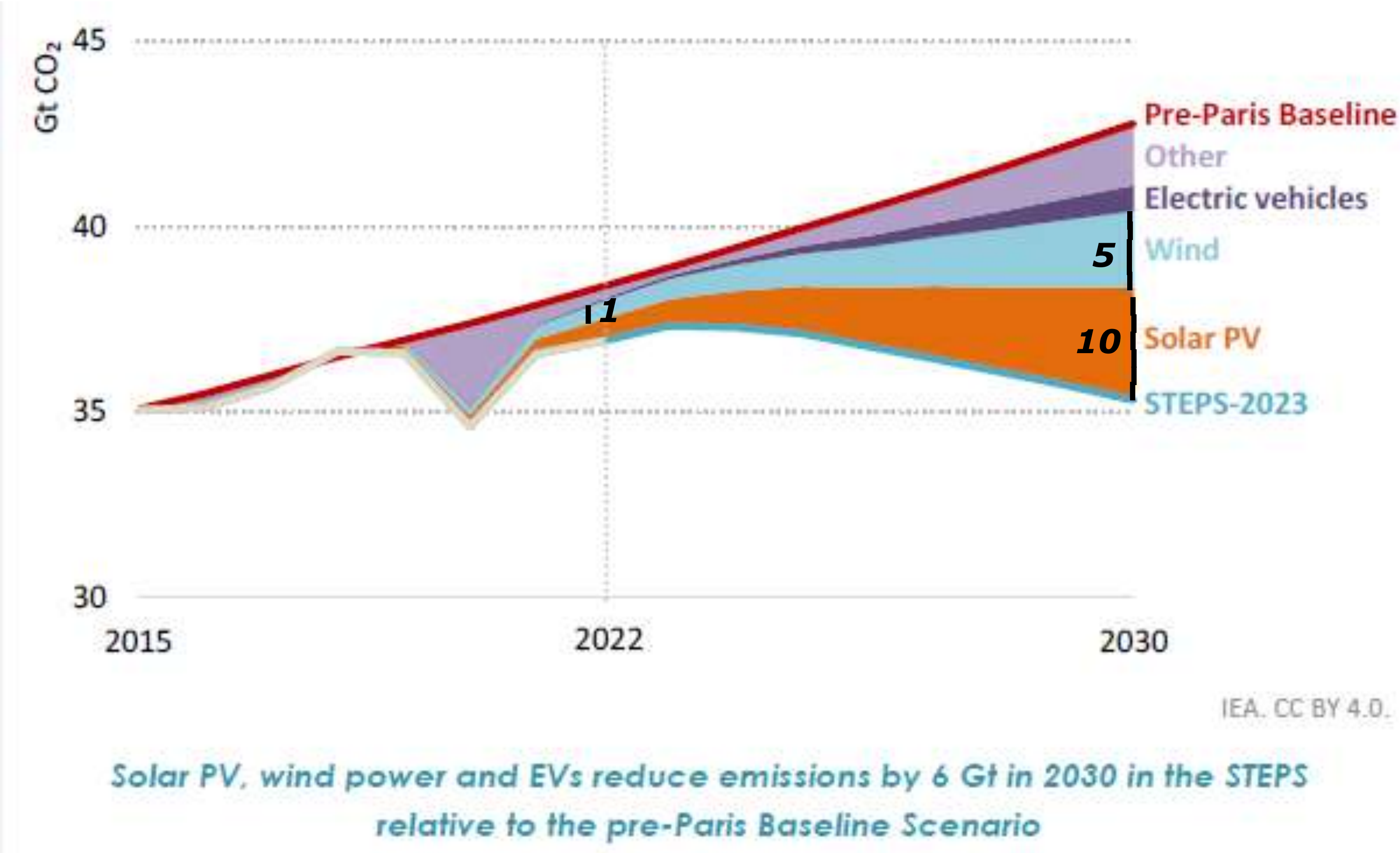
Non-specific, i.e., management, marketing, personnel can be interchanged.

Political vs economic considerations:
High labor intensity is of interest to local politics, but also constitutes disadvantage in economic competition.

Quality of the labor: higher qualification of the work-force → longer duration of the employment → higher long-term positive externalities.

Clean Energy Potential For Decarbonization

DOE: US wind settles at 7%; 2021-2030: +3GW/a; 2031-2050: +8GW/a



Stated Energy Policy Scenarios (STEPS) provides an outlook based on the latest policy settings, including energy, climate and related industrial policies.

Fin Hydro