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,

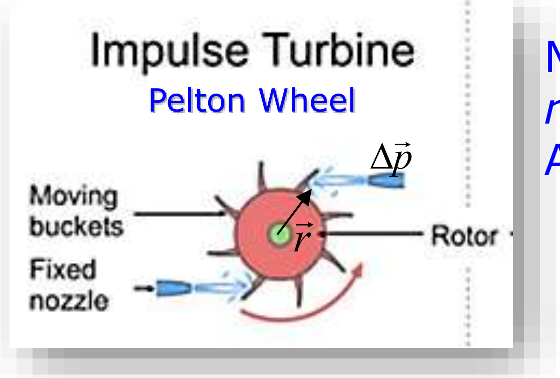
- World/US hydro-electricity generation,
  - Construction cost, electricity price,
  - Consumption,

- 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

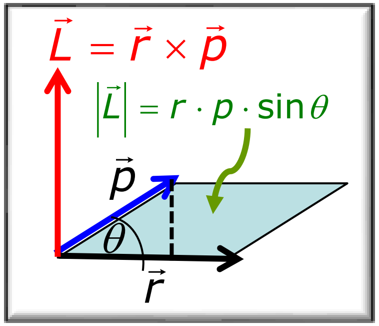
Power Generation in Impulse Turbines



Momentum transfer Δp by flow of *mass* impinging ⊥ on bucket plane C, Angular momentum

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

Mass density $\rho_m = m\rho$; *flux* $j(u) = \rho\cdot u$



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

Bucket area A_c *is hit per* **Δt** *by (velocity jet u, bucket* u_C*)*

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

$(u-u_c)$ = *speed relative to bucket*
initally $u_c \ll u$, *increases in time.*

$\to \boxed{\textit{Transfer } |\Delta p| = 2p \textit{ to cup in } \Delta t} \to \boxed{\text{Force } F = \Delta p/\Delta t}$

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

Example of dissipative force

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

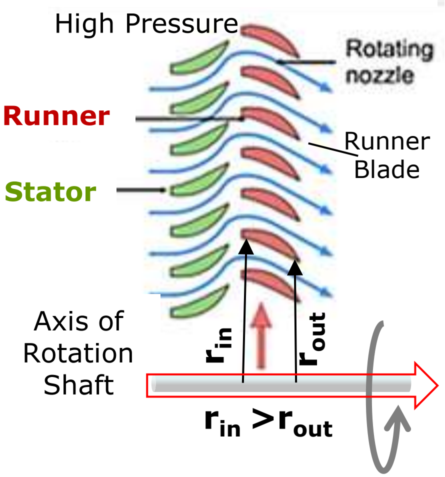
Power transferred to bucket: $\boxed{P = F\cdot u_c = \left[2\rho_m A_c\right](u-u_c)^2\cdot u_c}$

Rot speed of bucket increases, maximum power transfer $P_{\max}$ → $\boxed{u_c = u/3}$

$$P_{\max} = \frac{2}{27}\left[\rho_m\cdot A_c\right]\cdot u^3 = \frac{4}{27}\underbrace{\left[\frac{m}{2}\cdot u^2\right]}_{e_{kin}}\cdot\underbrace{(\rho\cdot u\cdot A_c)}_{\dot{Q}_\# = j\cdot A_C} \to \boxed{P_{\max} = \frac{4}{27}\dot{Q}_\#\cdot\left(\frac{m}{2}\cdot u^2\right)} \quad \boxed{\varepsilon \lesssim 16\%}$$

Angular Momentum Transfer in Reaction Turbines

Reaction Turbine



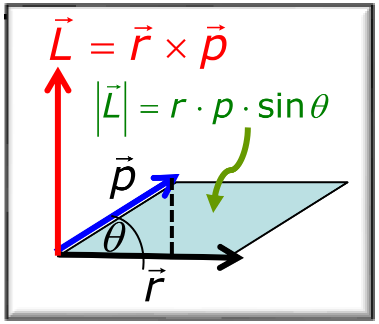
Mass deflection → recoil momentum $\Delta\vec{p}$ → torque $M = \Delta L/\Delta t = \left|\vec{r}\times\vec{F}\right|$

Torque speeds up turbine rotation → increased $\Delta\vec{L}_T$

Exiting fluid has lost this angular momentum.

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

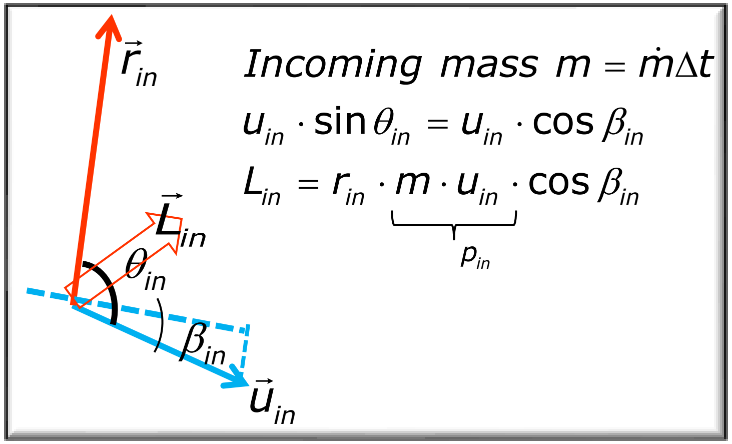
all parallel, rel. rot axis



$\vec{L} = \vec{r}\times\vec{p}$

$\left|\vec{L}\right| = r\cdot p\cdot\sin\theta$

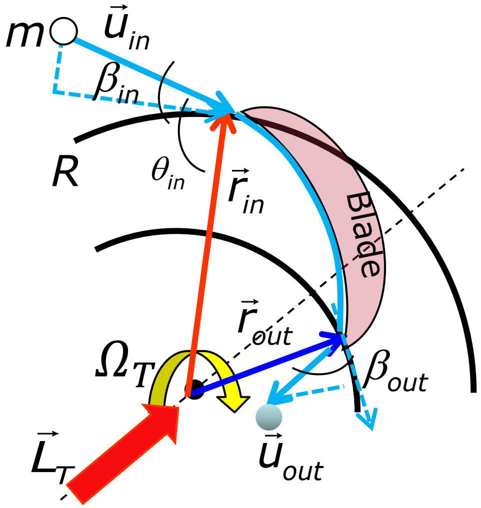
Outer vector product of two vectors $\vec{r}$ and $\vec{p}$



Incoming mass $m = \dot{m}\Delta t$

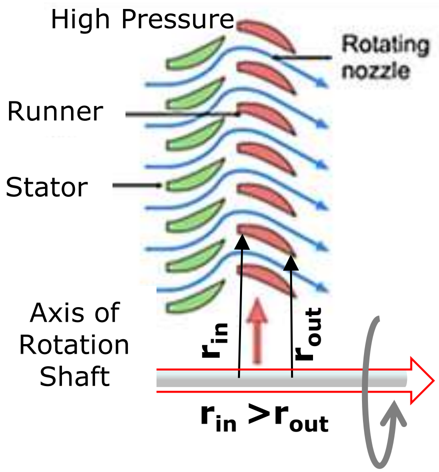
$$u_{in}\cdot\sin\theta_{in} = u_{in}\cdot\cos\beta_{in}$$

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



Angular Momentum Transfer in Reaction Turbines

Reaction Turbine



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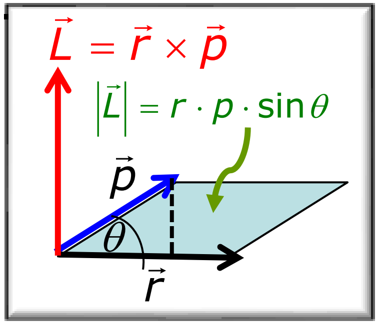
Torque speeds up turbine rotation → increased $\Delta\vec L_T$

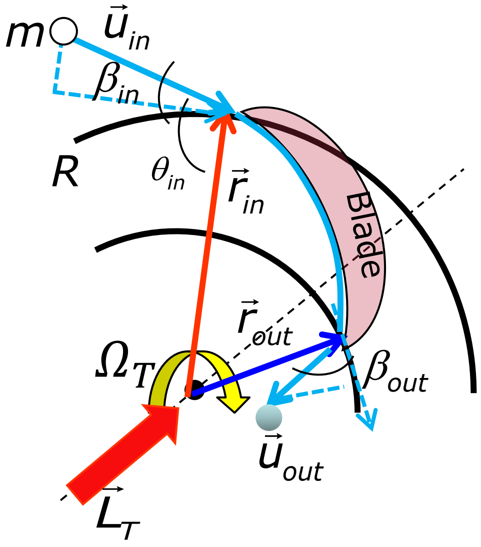
Exiting fluid has lost this angular momentum

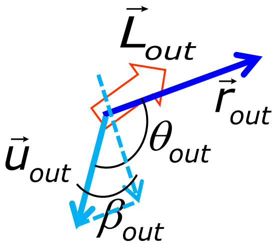
$$\boxed{\Delta\vec L_T = \vec L_{in} - \vec L_{out}}$$

all parallel,
rel. rot axis



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





Outgoing mass $m = \dot m \Delta t$

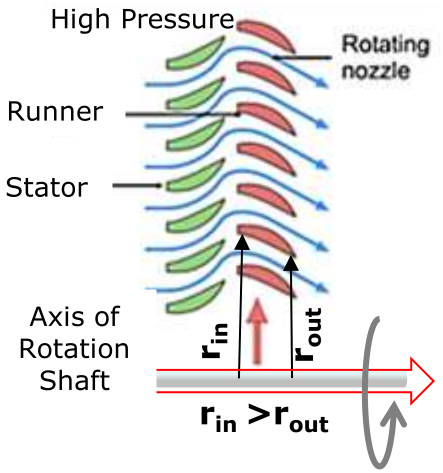
$$u_{out} \cdot \sin\theta_{out} = u_{out} \cdot \cos\beta_{out}$$

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

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

Angular Momentum Transfer in Reaction Turbines

Reaction Turbine



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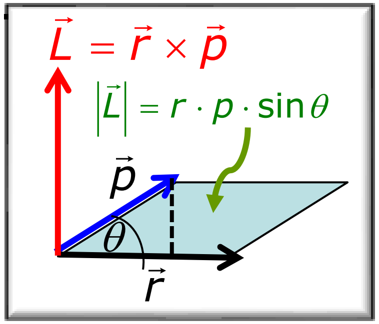
$$\boxed{\Delta\vec{L}_T = \vec{L}_{in} - \vec{L}_{out}}$$

all parallel, rel. rot axis



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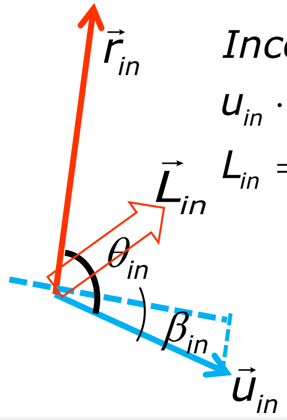
Outer vector product of two vectors $\vec{r}$ and $\vec{p}$



Incoming mass $m = \dot{m}\Delta t$

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

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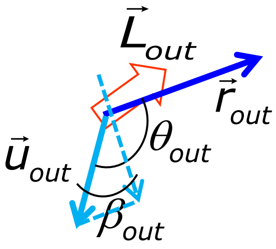
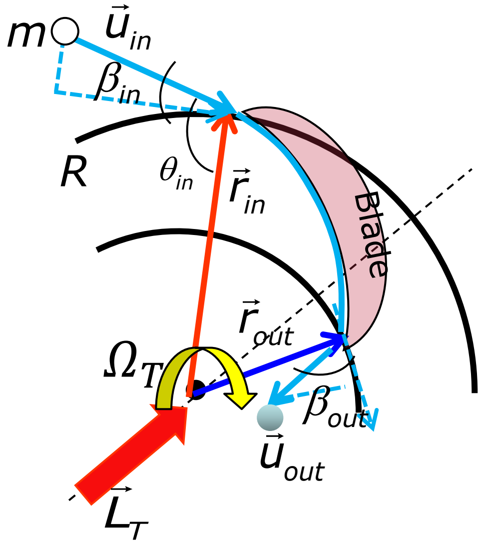


Outgoing mass $m = \dot{m}\Delta t$

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

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

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



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

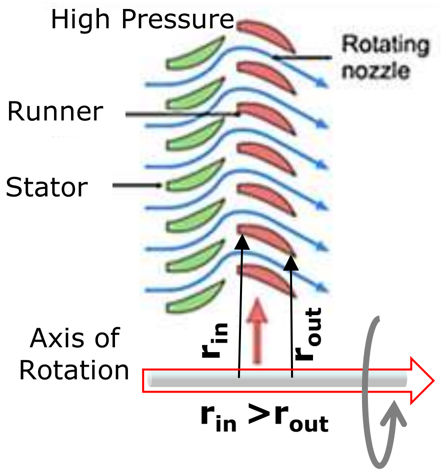
Power $P = M\cdot\Omega_T$; *Mass flow* $\dot{m} = \rho_m\cdot\dot{Q}$

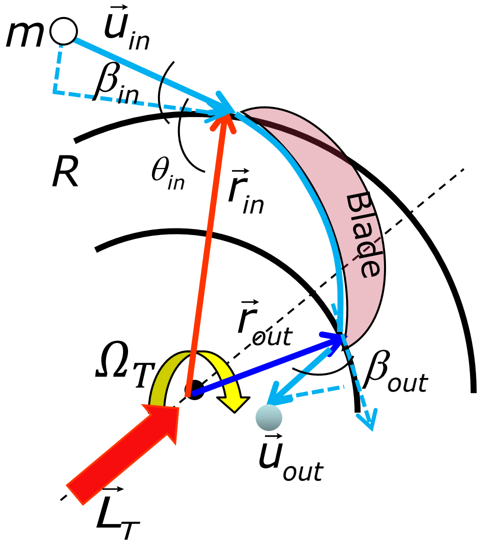
Euler's Turbine Equation

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

Angular Momentum Transfer in Reaction Turbines

Reaction Turbine





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

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

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

$$\dot{Q} = dV/dt$$

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

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.

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

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

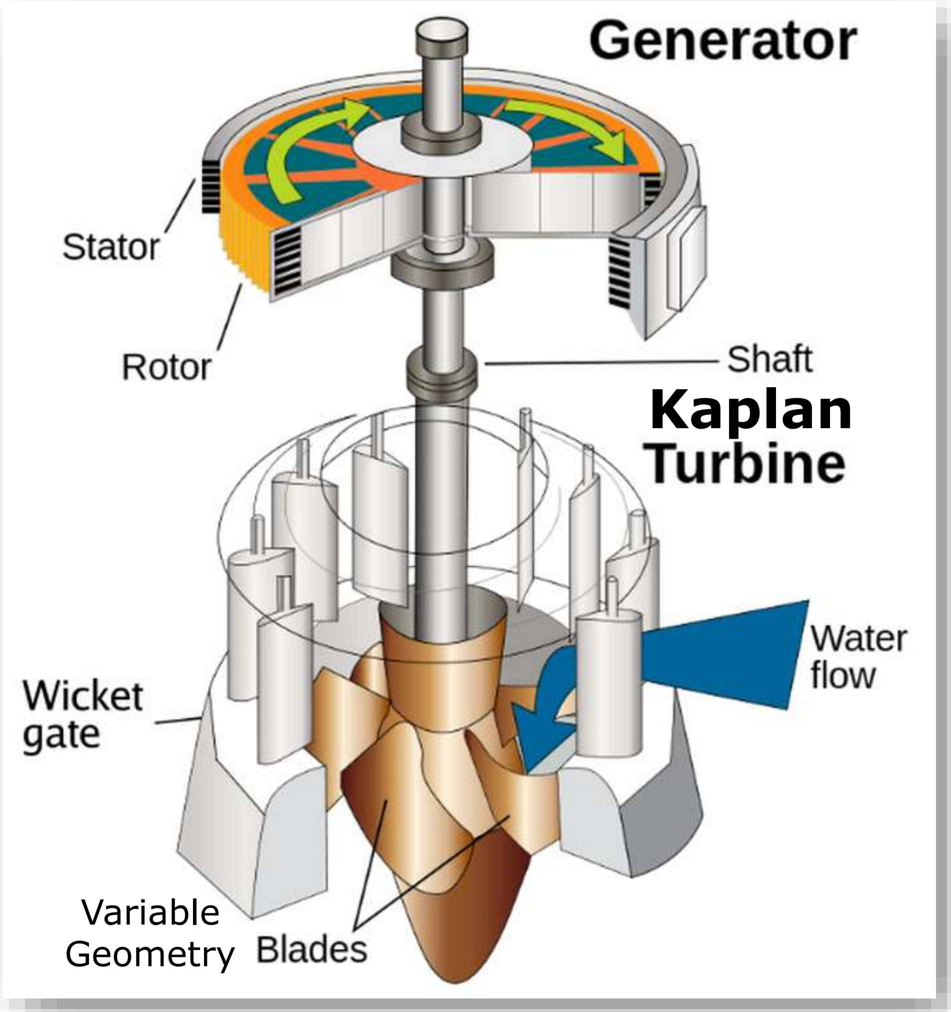
$R =$ injection radius for turbine,

$\left(u_{in}\right)_{tang} =$ 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.

Reaction Turbine Blade Arrangements

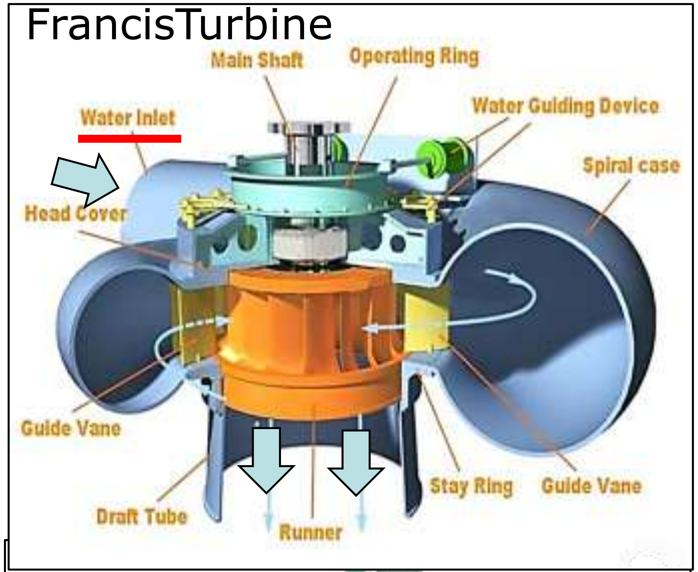


Wikipedia

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"

Popular Types Reaction Turbines

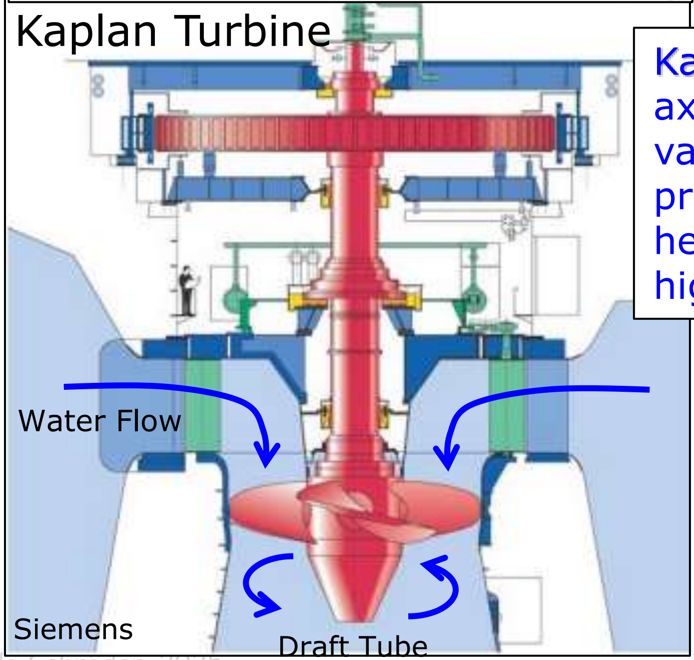


Most hydro turbines are impact or reaction type.

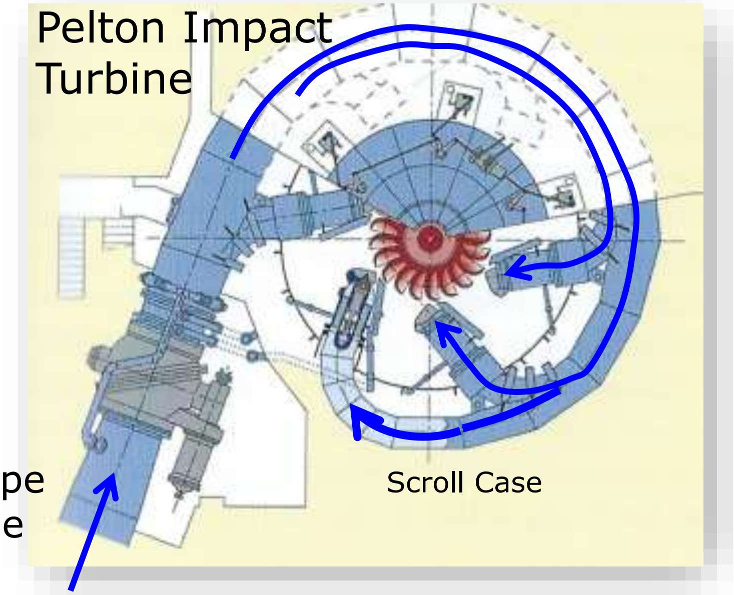
Francis Turbine, radial inflow, dia 0.5- 6 m
Fully submerged, horizontal or vertical modes.
→ Axial outflow.

Popular design, versatile & useful for very different (mid-to-high) effective heads

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

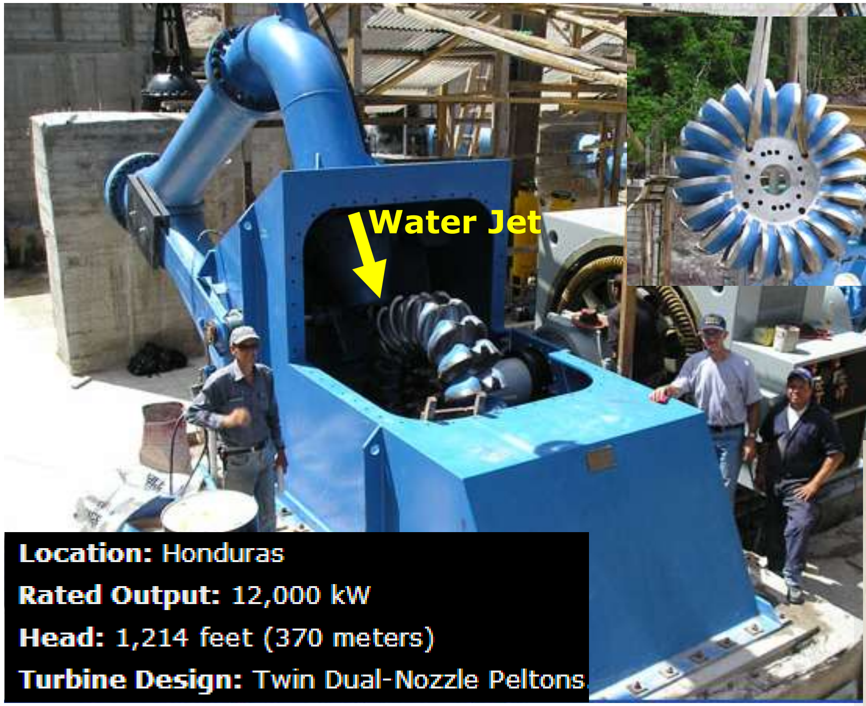


Kaplan Turbine, axial inflow, variable-pitch propeller. Low head (<50m), high flow.



Scroll type inlet tube

Francis & Pelton Hydro Turbines



Location: Honduras
Rated Output: 12,000 kW
Head: 1,214 feet (370 meters)
Turbine Design: Twin Dual-Nozzle Peltons

Upper Swift Creek
Location: Wyoming, USA
Rated Output: 910 kW
Head: 140 feet (42.7 meters)
Turbine Design: Francis

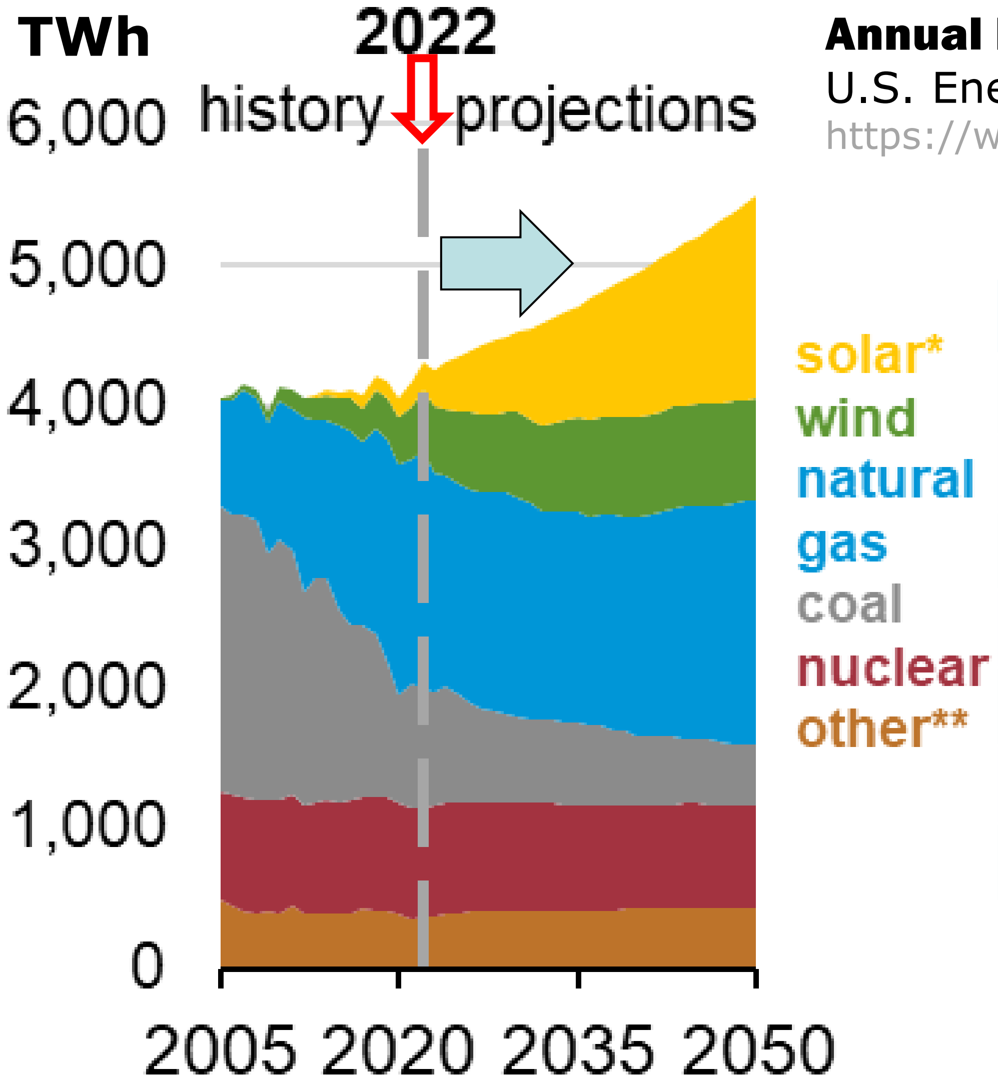
Kaplan & Francis Hydro Turbine Rotors

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.

Annual U.S. Electricity Production

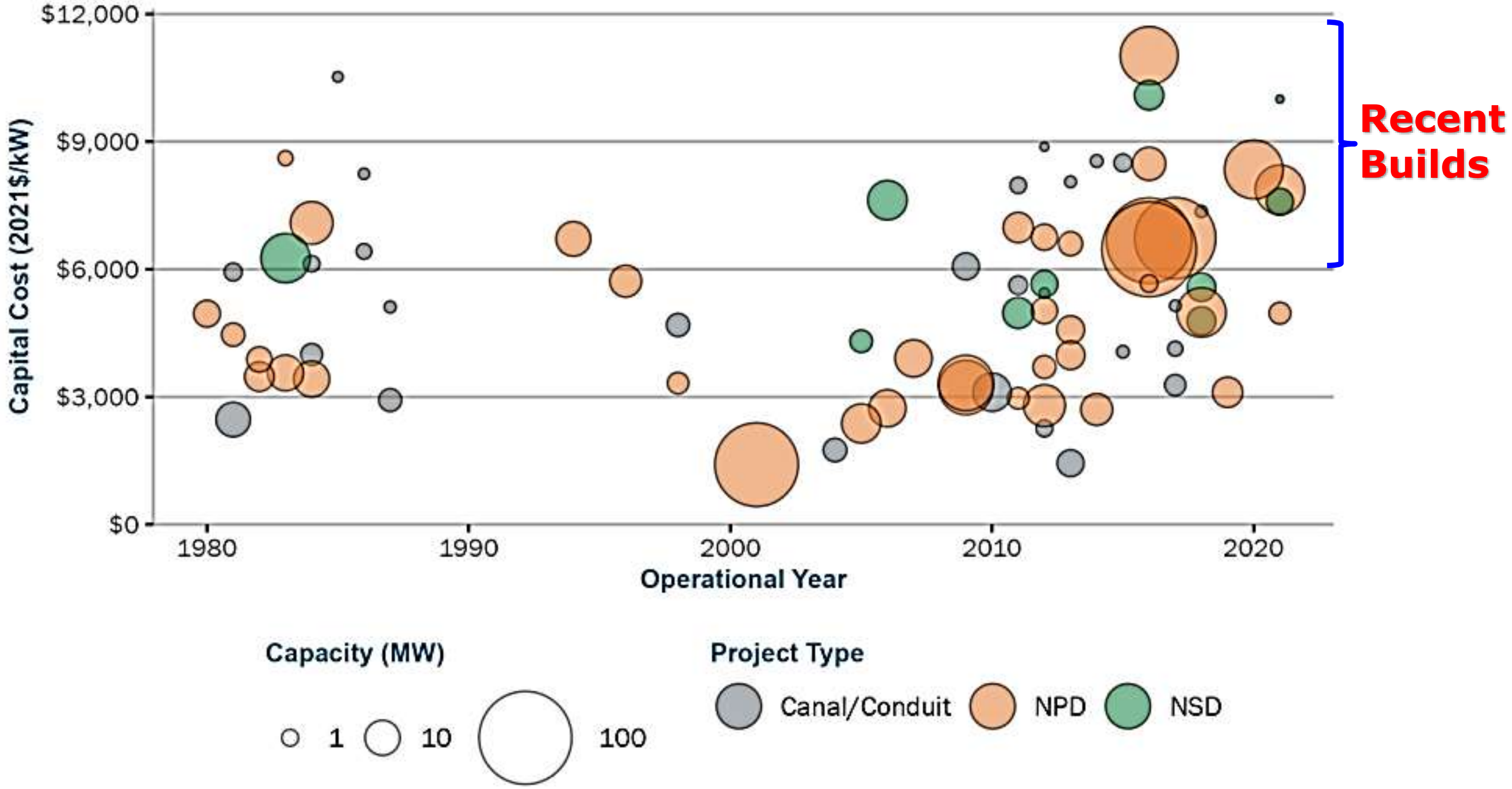


Annual Energy Outlook **AEO2024**
U.S. Energy Information Administration
https://www.eia.gov/electricity/data/browser/

US 2024 GWh	Source
453.5E+03	Wind
219.8E+03	Solar
242.9E+03	Hydroelectric
781.9E+03	Nuclear
1,869.9E+03	Nat. Gas
652.2E+03	Coal
3,771.2E+03	**Total**

(-10%)

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.

Agenda

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  - Hydrological cycle,
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  - 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.

Reading Assignments
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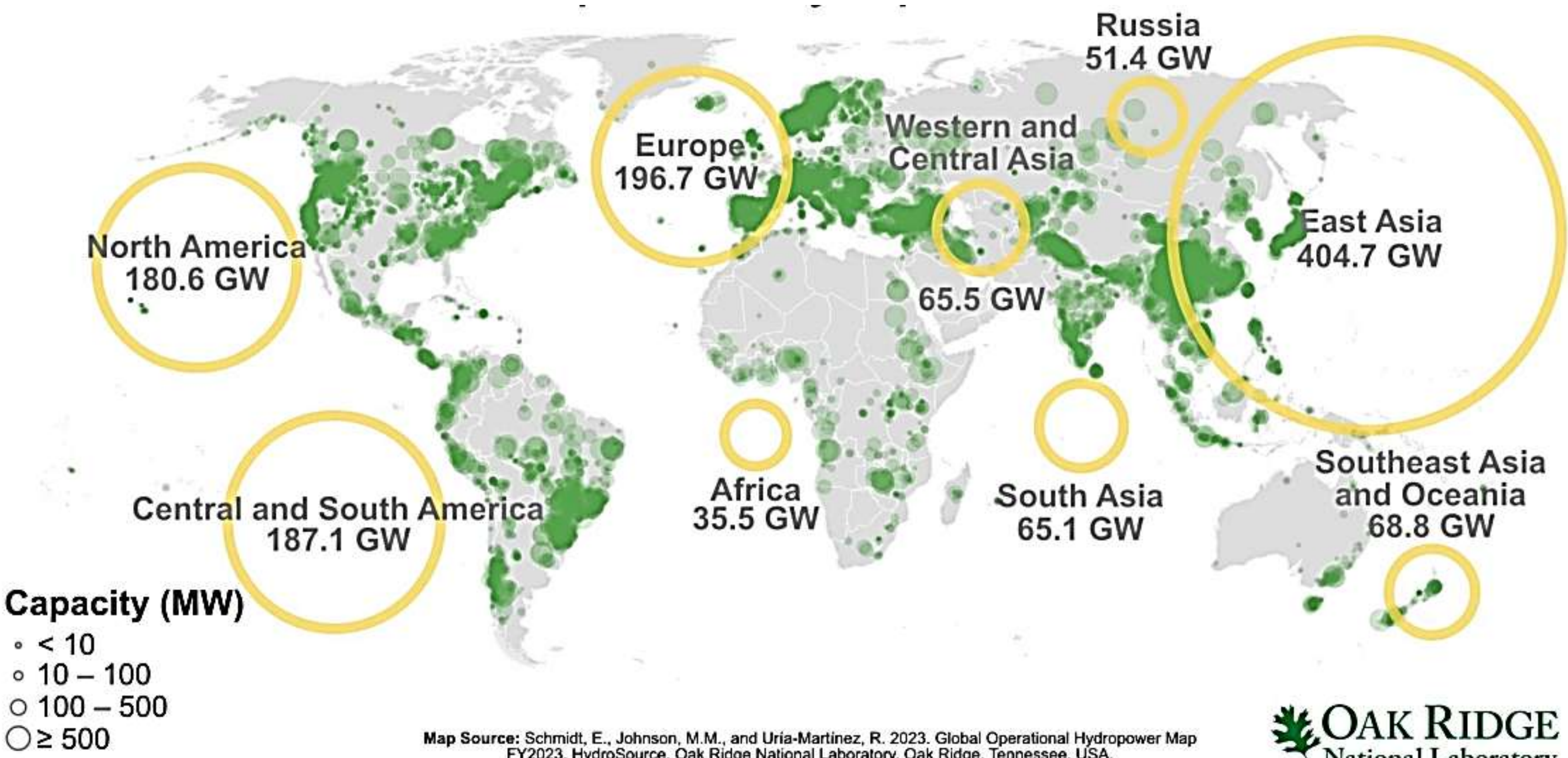
- Next topic: Power from Biomass

2023 World Operational Hydropower Plants

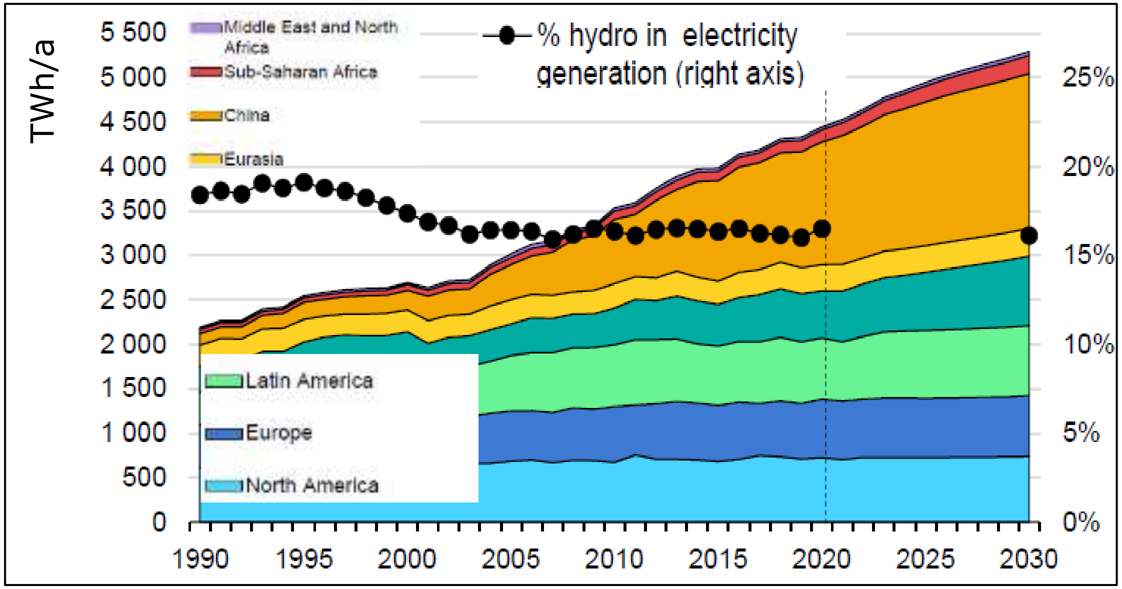


Map Source: Schmidt, E., Johnson, M.M., and Uría-Martínez, R. 2023. Global Operational Hydropower Map FY2023. HydroSource, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.
DOI: 10.21951/HMR_GlobalMaps/1972207

OAK RIDGE
National Laboratory

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/Outlook



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

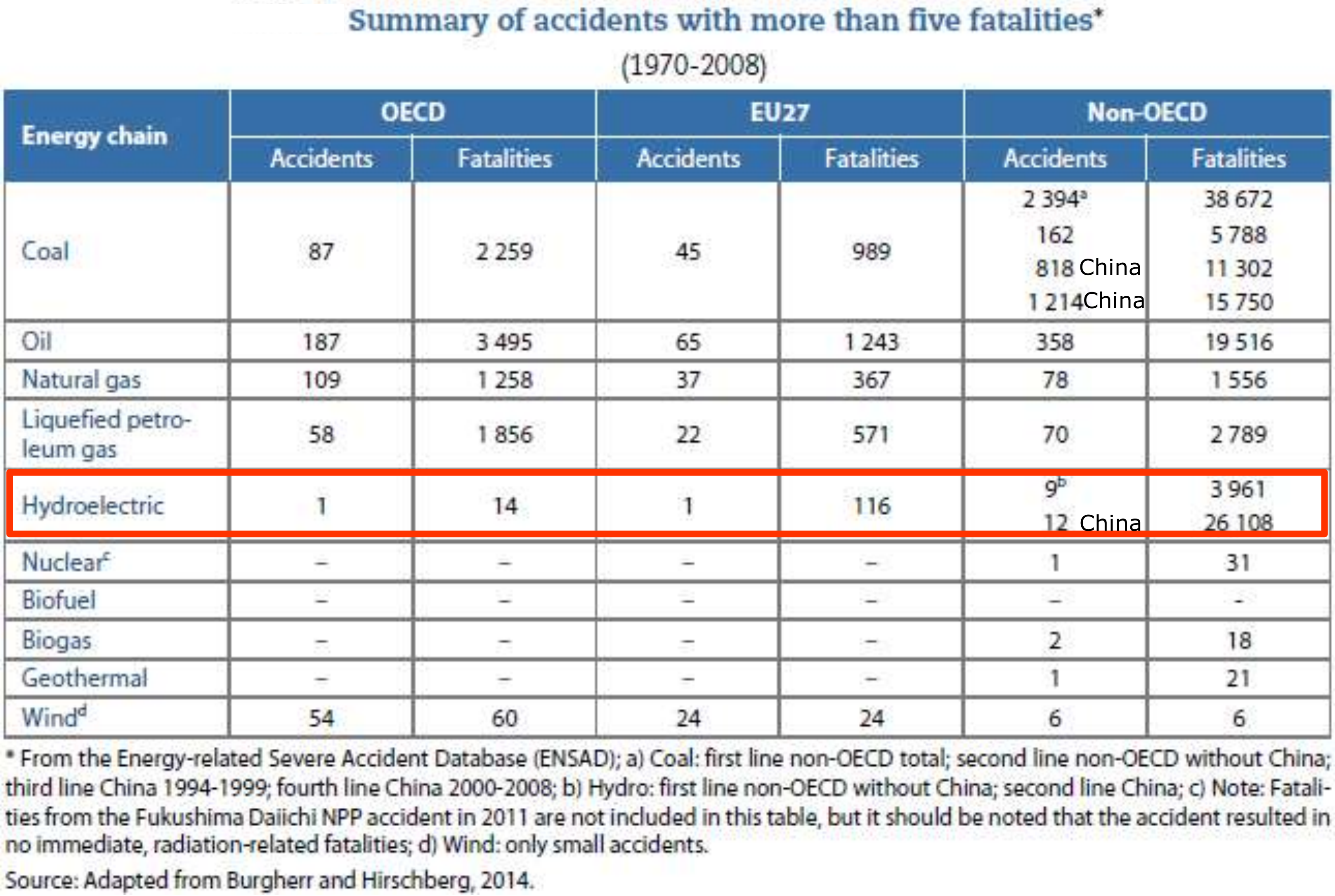
Type: Concrete Gravity Dam
Cost: Official cost US$ 25 B
(actual cost believed to be higher)
Construction: 1993 - 2009
Reservoir: 660km long, 632 km^2.
Head: 175 m.

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]

Energy-Related Accidents in Perspective



Summary of accidents with more than five fatalities*

(1970-2008)

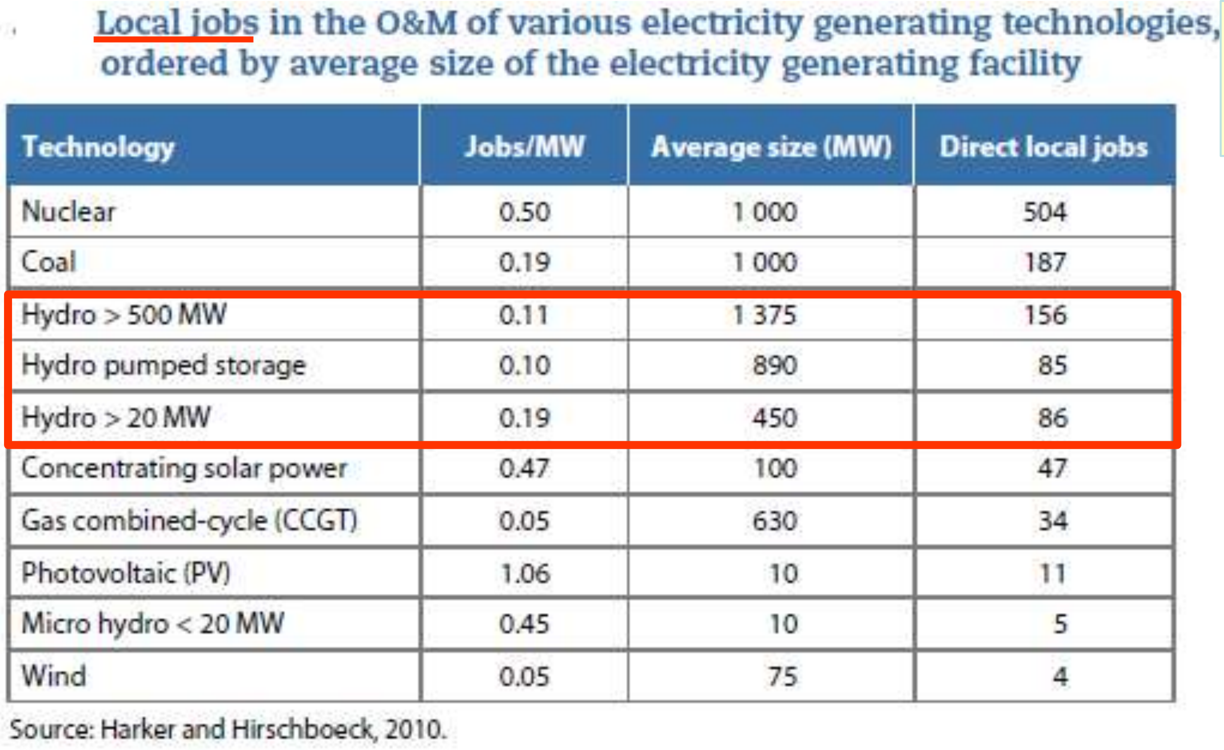
Energy chain	OECD		EU27		Non-OECD	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	87	2 259	45	989	2 394[a] 162 818 China 1 214China	38 672 5 788 11 302 15 750
Oil	187	3 495	65	1 243	358	19 516
Natural gas	109	1 258	37	367	78	1 556
Liquefied petroleum gas	58	1 856	22	571	70	2 789
Hydroelectric	1	14	1	116	9[b] 12 China	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.

2023: **10–11 Sept. 2023, Derna** Libya: agricultural hydro accident, many fatalities, not included.

Employment in Energy Technology 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.

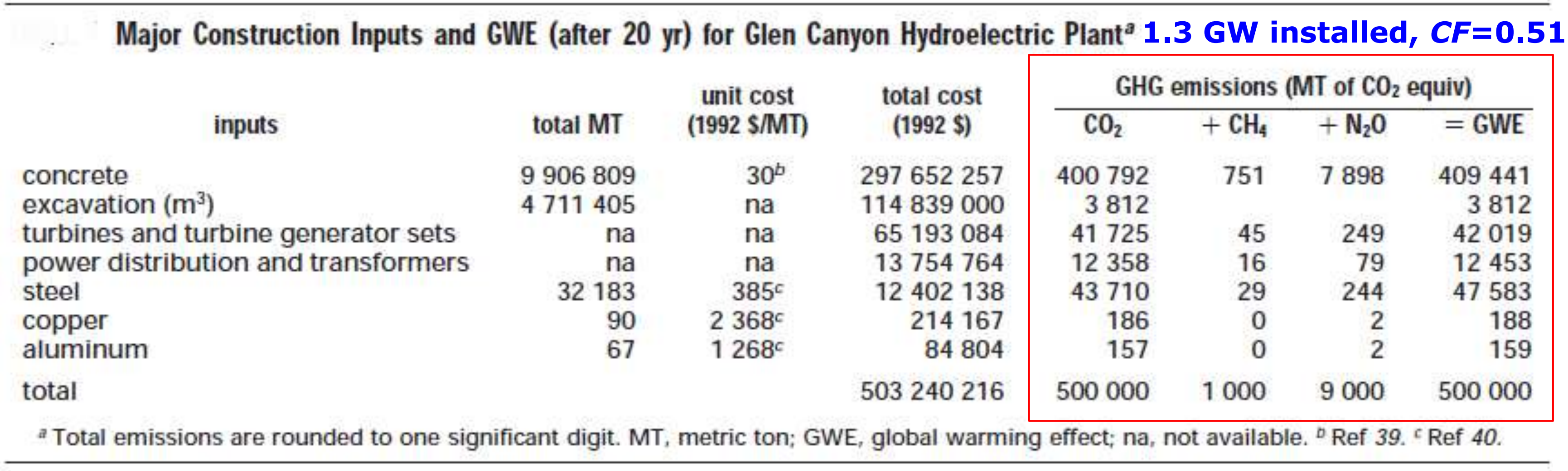
Quality of the labor: higher qualification of the work-force → longer duration of the employment → higher long-term positive externalities.

External Global Warming Effect of Hydro Dams

Example: 1.3 GW Glen Canyon Dam, Reservoir 653 km^2, 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 (m^3)	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)

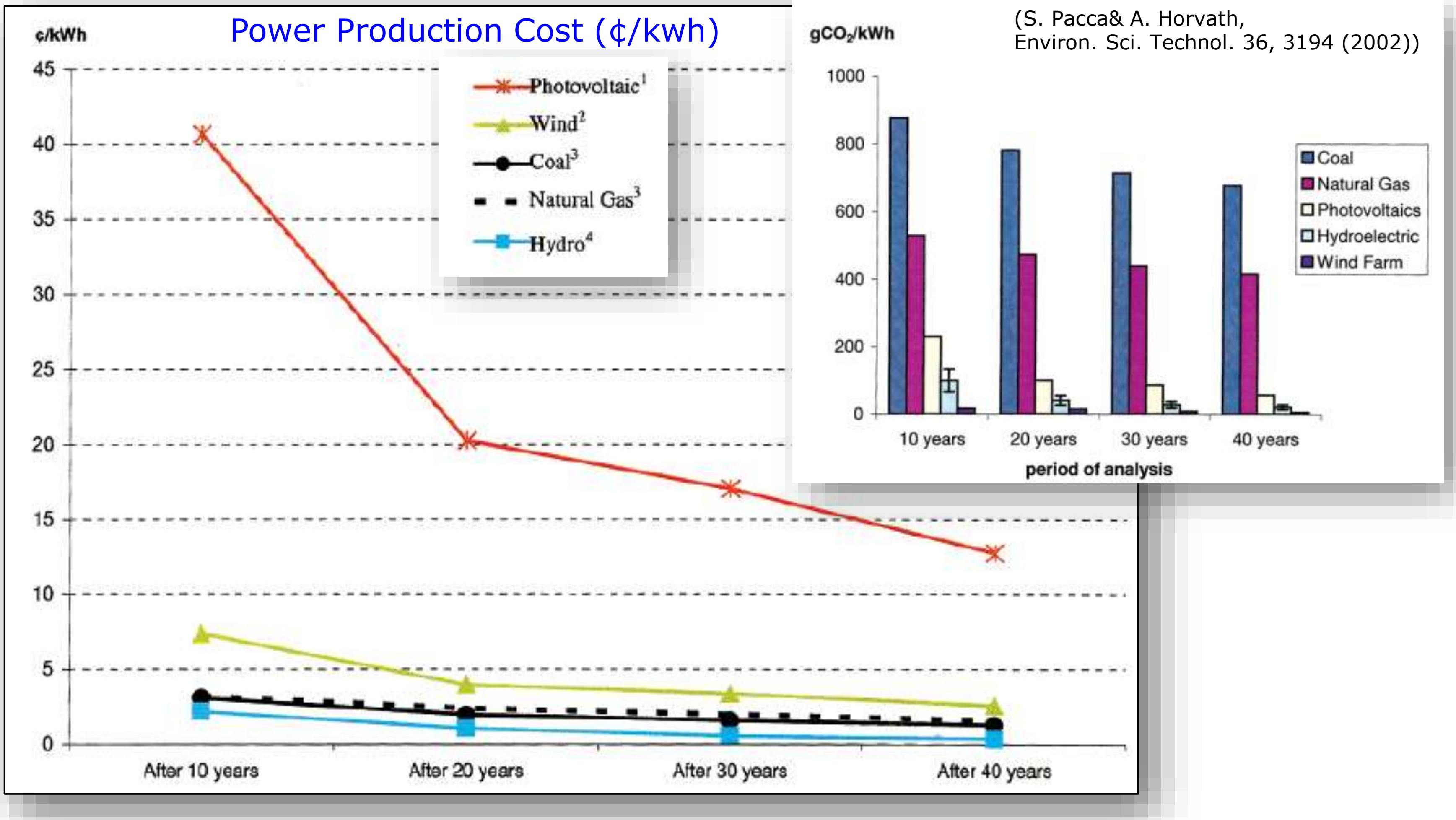
Hydropower Strategic Issues

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.

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.



Power Production Cost (¢/kwh)

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

Fin Hydro