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SUSTAINABLE ENERGY

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Nuclear Engineering Dept.

HYDROPOWER

HYDRO POWER – A CASE STUDY

- Some facts and figures
- Large-scale versus small scale
- High head versus low–head
- Energy conversion technology
- Environmental and social impacts
- Economic issues

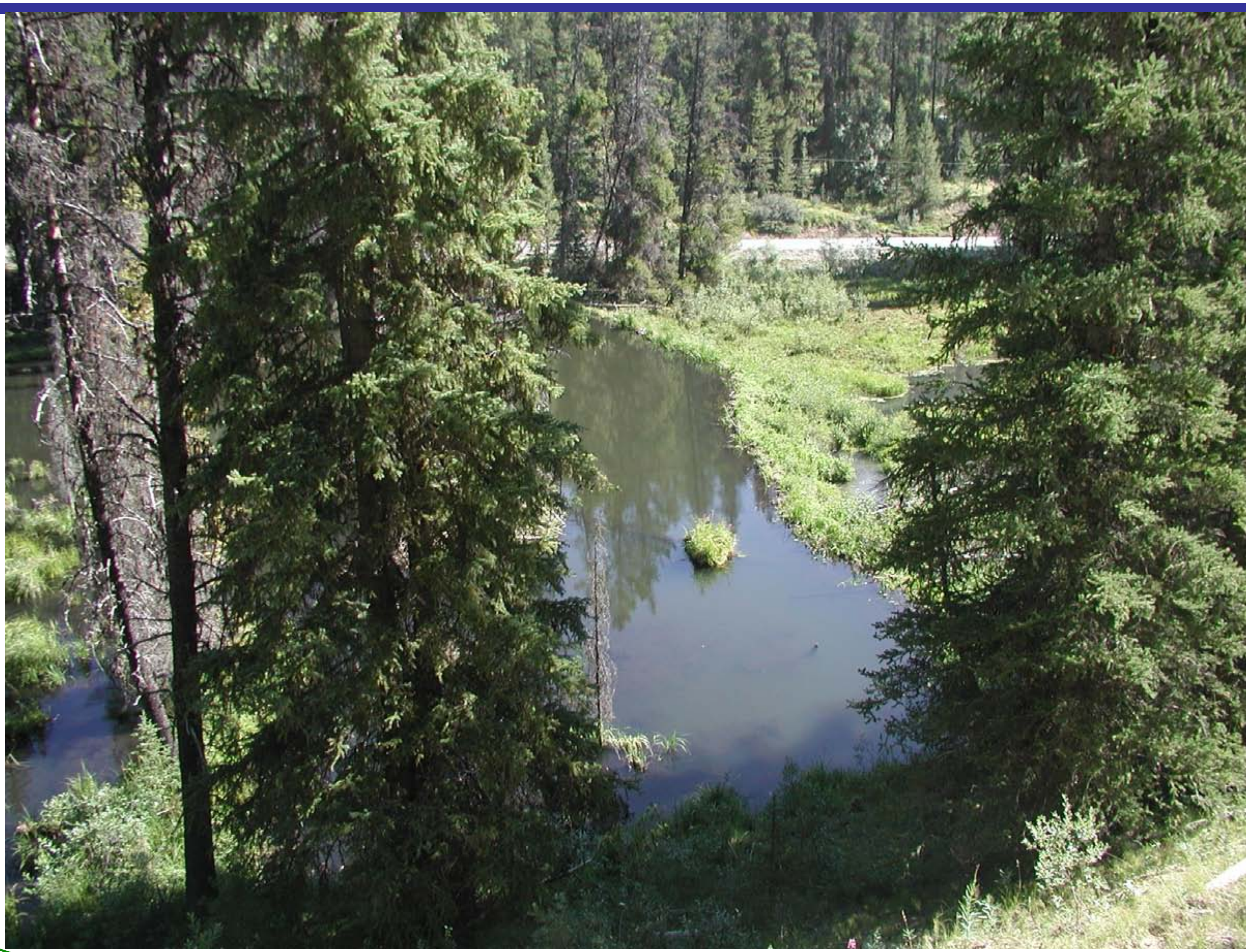
FOUR TYPES OF HYDROPOWER SYSTEMS

1. Impoundment Involving Dams: e.g., Hoover Dam, Grand Coulee
2. Diversion or Run-of-River Systems: e.g., Niagara Falls
3. Pumped Storage
   - Two way flow
   - Pumped up to a storage reservoir and returned to lower elevation for power generation
4. Tidal: e.g., la Rance

BOSTON BACK BAY

Photo by Peter Stevens on Flickr.

BC BEAVER DAM



HYDRO-QUÉBEC PRODUCTION

- 97% renewable energy
- 57 hydroelectric generating stations (35,647 MW)
- 26 reservoirs
(capacity of 175 TWh / year)
- 1 nuclear power plant
- Annual investment: $2 billion

CANIAPISCAU RESERVOIR

Aerial photo of Caniapiscau Reservoir removed due to copyright restrictions.

Caniapiscau Reservoir is a man-made lake, created as part of the La Grande Complex (James Bay) Hydro-electric Project.

http://www.ilec.or.jp/database/nam/nam-35.html

THREE GORGES DAM

Image by Jesse Allen, Earth Observatory, using ASTER data made available by NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team. Via NASA Visible Earth, Goddard Space Flight Center.

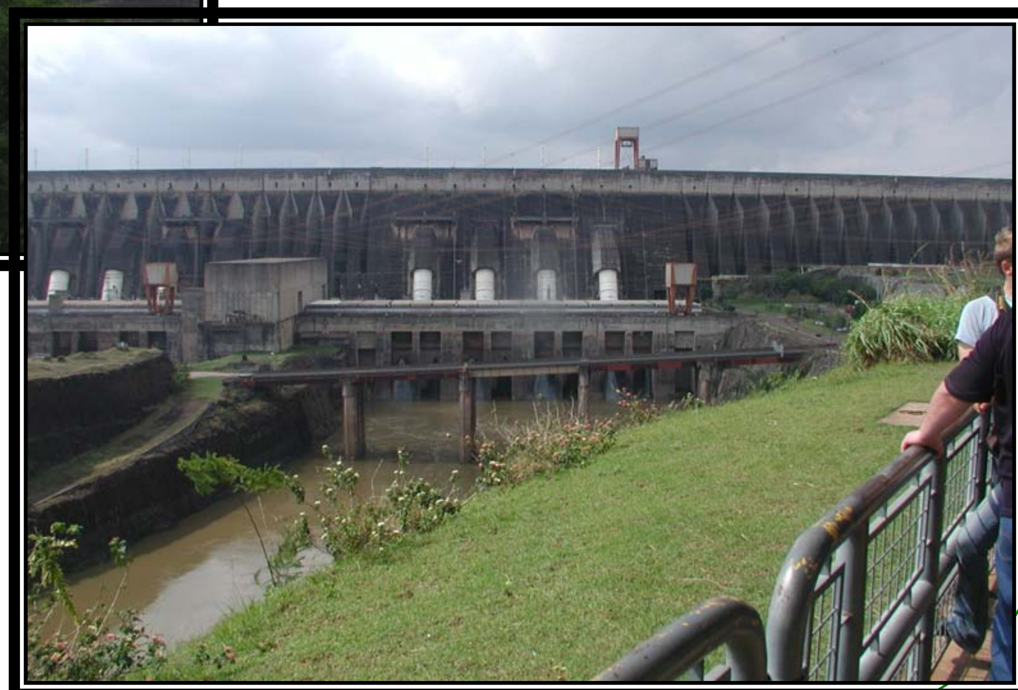
BONNEVILLE DAM

DORDOGNE DAM

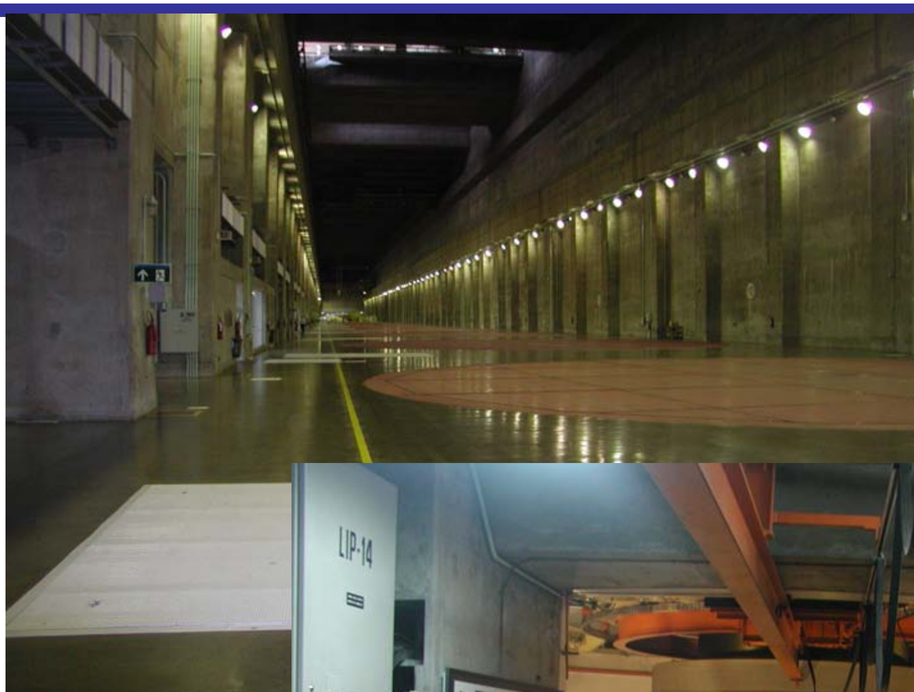
ITAIPU DAM

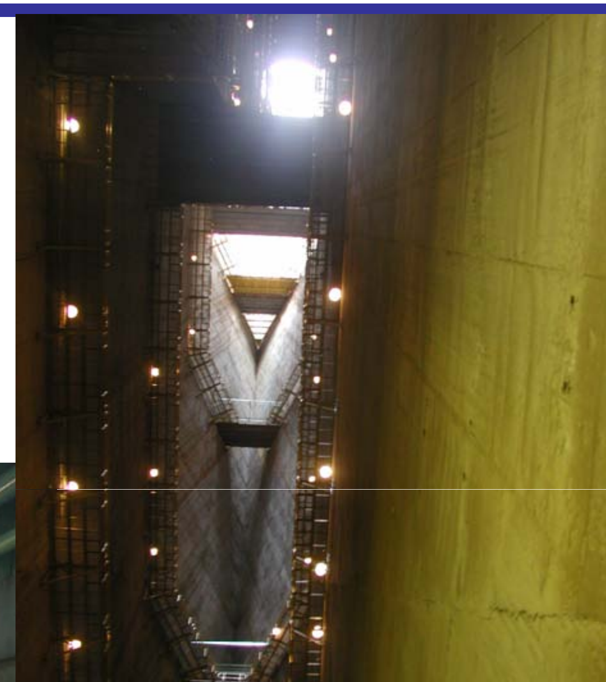
Photo by Herr stahlhoefer on Wikimedia Commons.

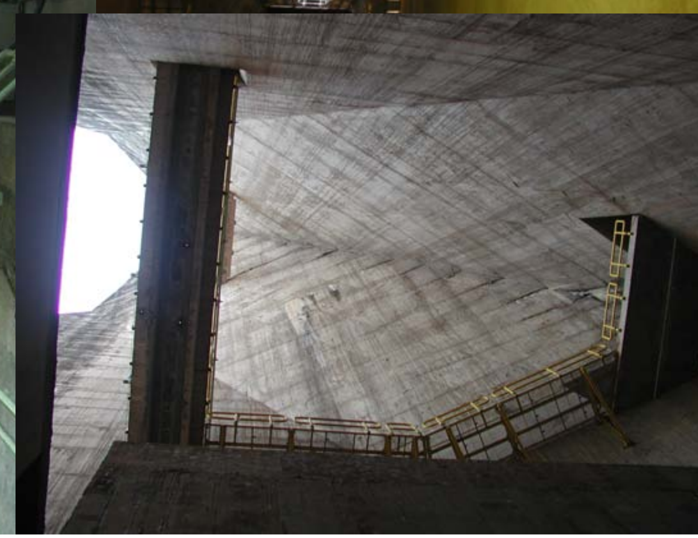
ITAIPU DAM



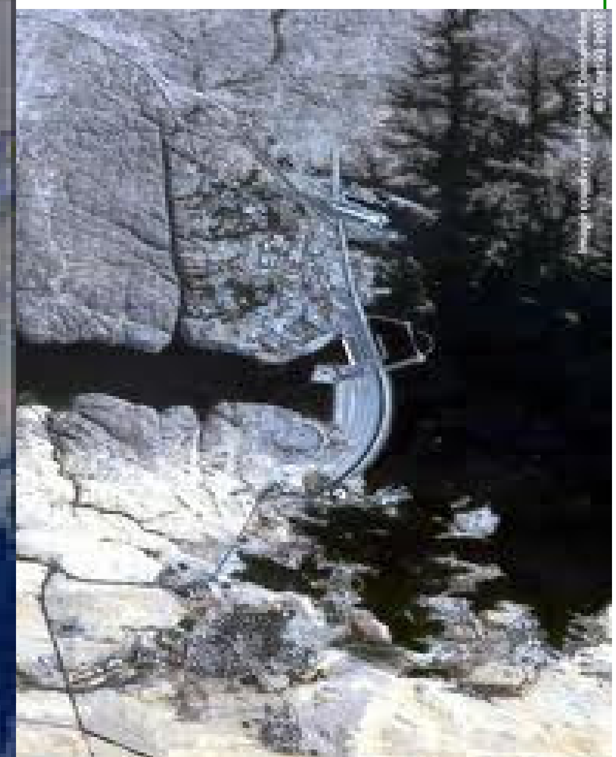
ITAIPU DAM







ASWAN DAM



Photos by Image Science & Analysis Laboratory, NASA Johnson Space Center and NASA Visible Earth, Goddard Space Flight Center.

COMMON FEATURES OF CONVENTIONAL HYDROPOWER INSTALLATIONS

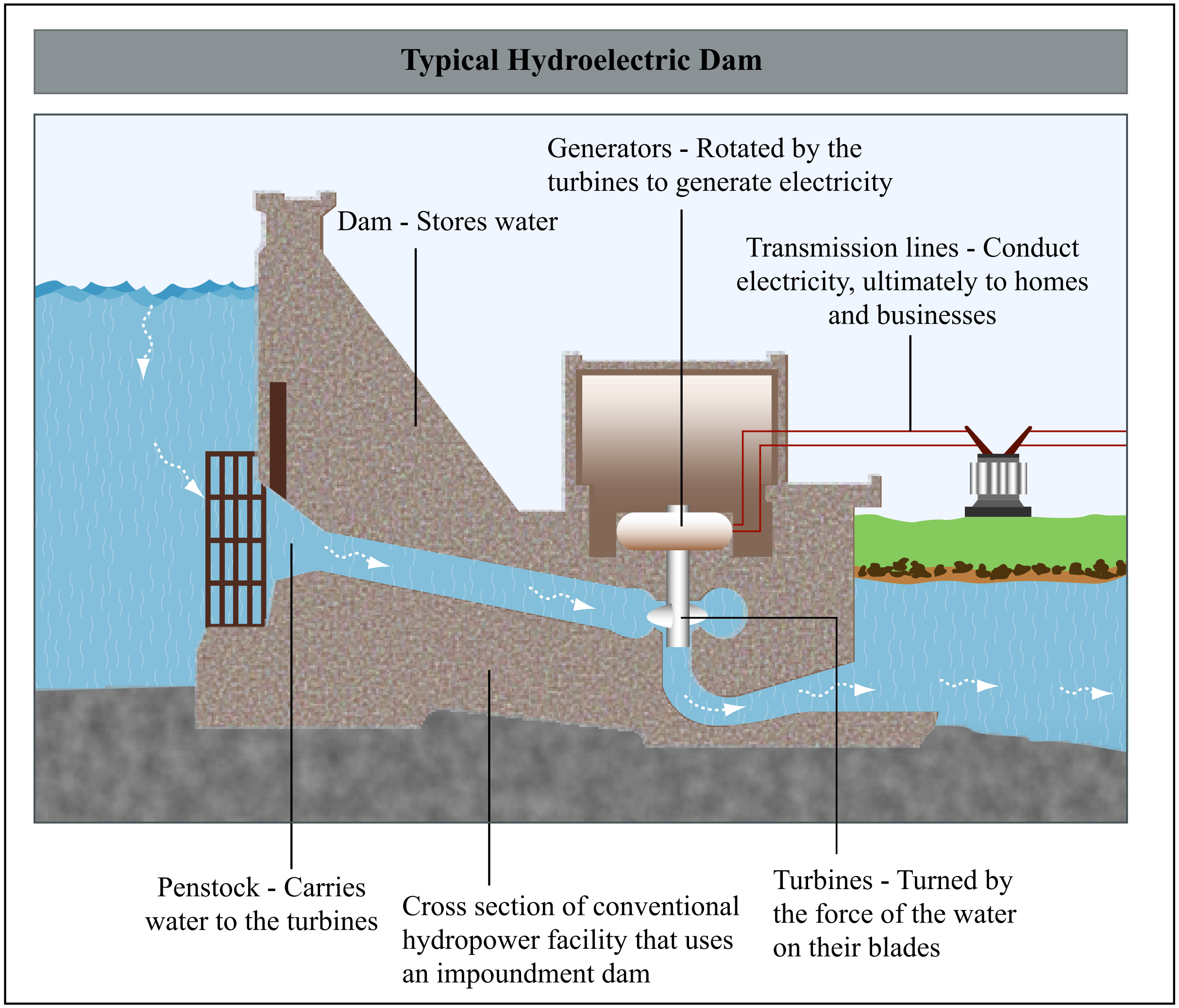
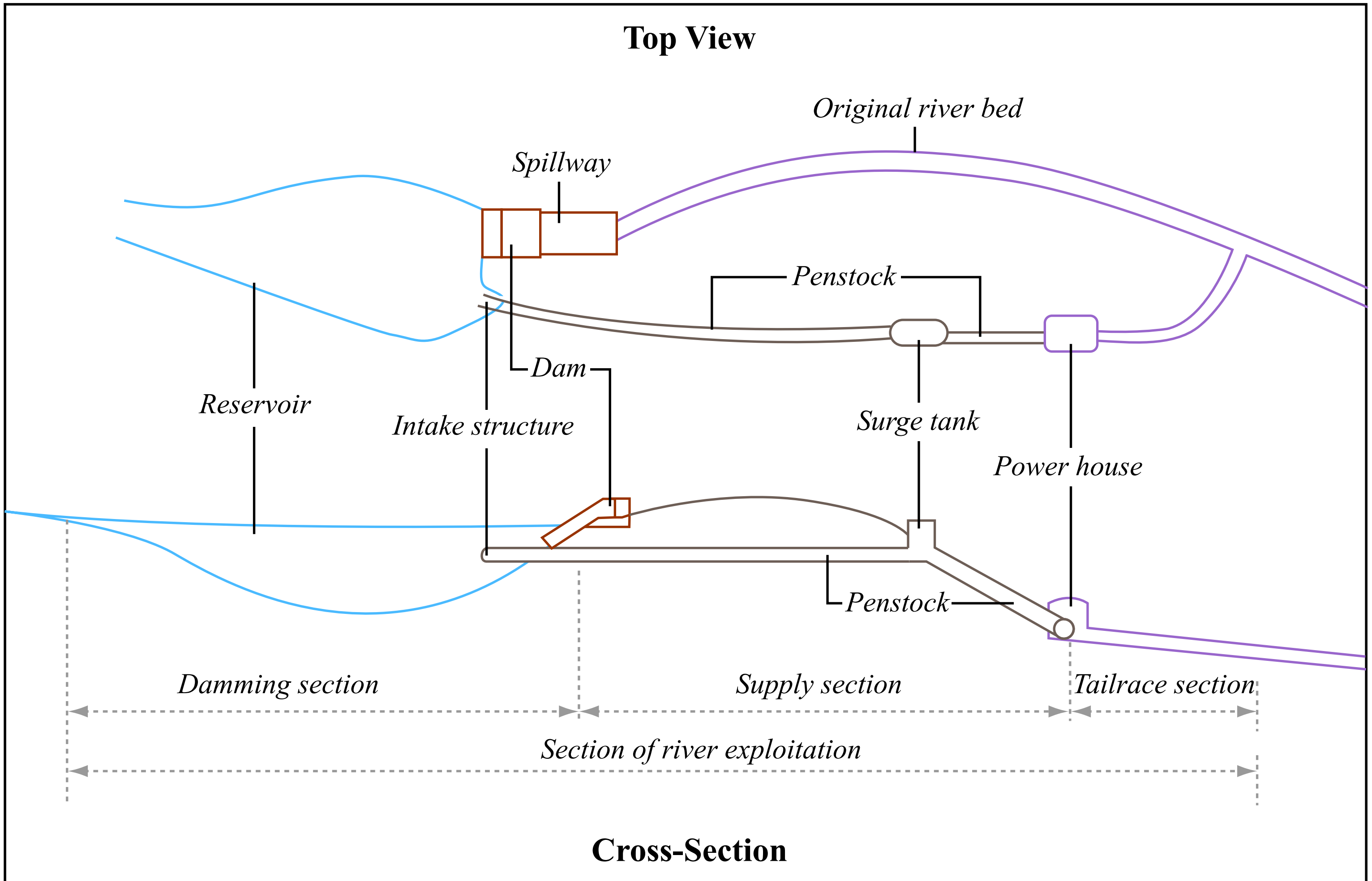


Image by MIT OpenCourseWare. Adapted from Tennessee Valley Authority.

CONVENTIONAL HIGH HEAD RUN-OF-RIVER HYDROPOWER, e.g., NIAGARA FALLS



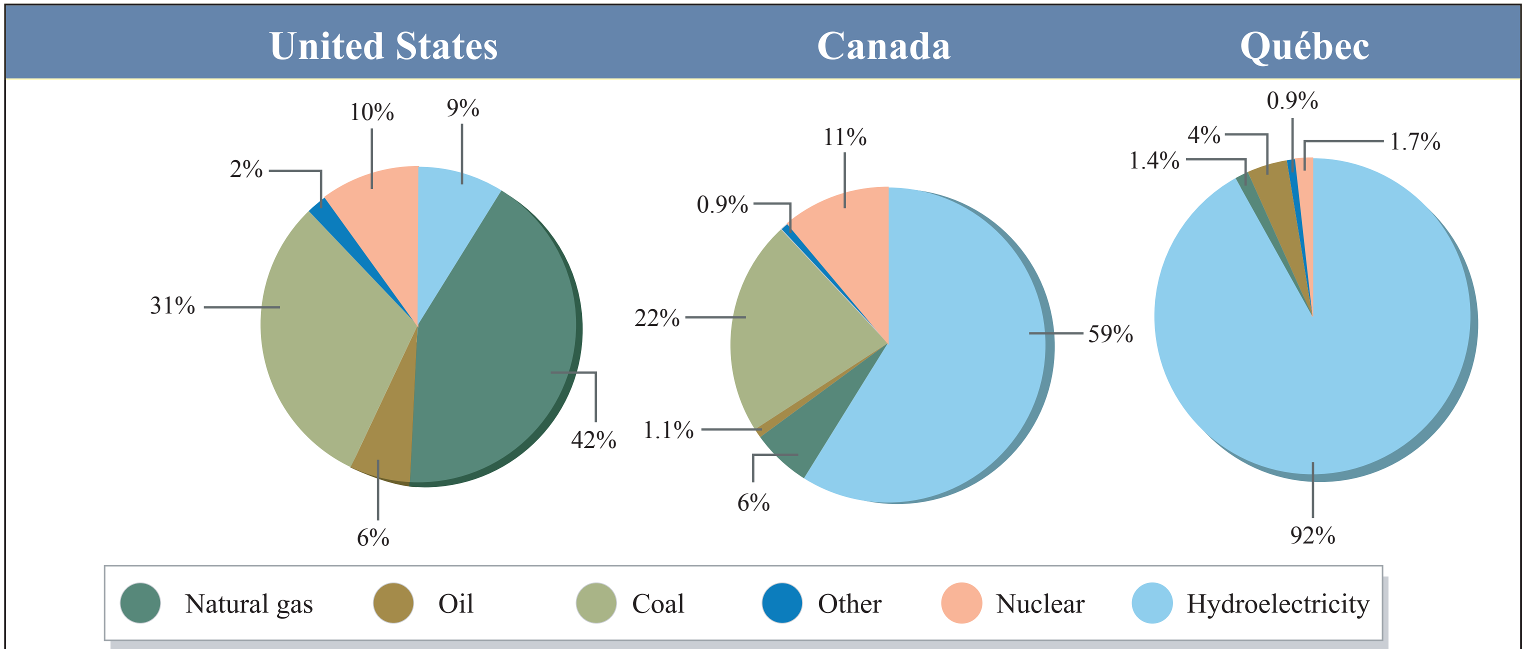
The characteristic components of a river-diversion hydroelectric plant.

Image by MIT OpenCourseWare.

HYDRO POWER – SOME FACTS AND FIGURES

- Current World Hydropower Production (2006)
  - ~ 3000 TWh -- about 20% of the world's electricity and about 88% of electricity from renewable sources
  - ~ 777 GWe of capacity in 150 countries
- US capacity 100,451 MWe (2009)
  - 78,951 MWe conventional hydro
  - 21,500 MWe pumped storage
  - About 8% of US electricity equivalent to 2.9 quads
  - Approximately 70% of US renewable energy
- Average Capacity/Availability Factor – 42% (~6% of total capacity)

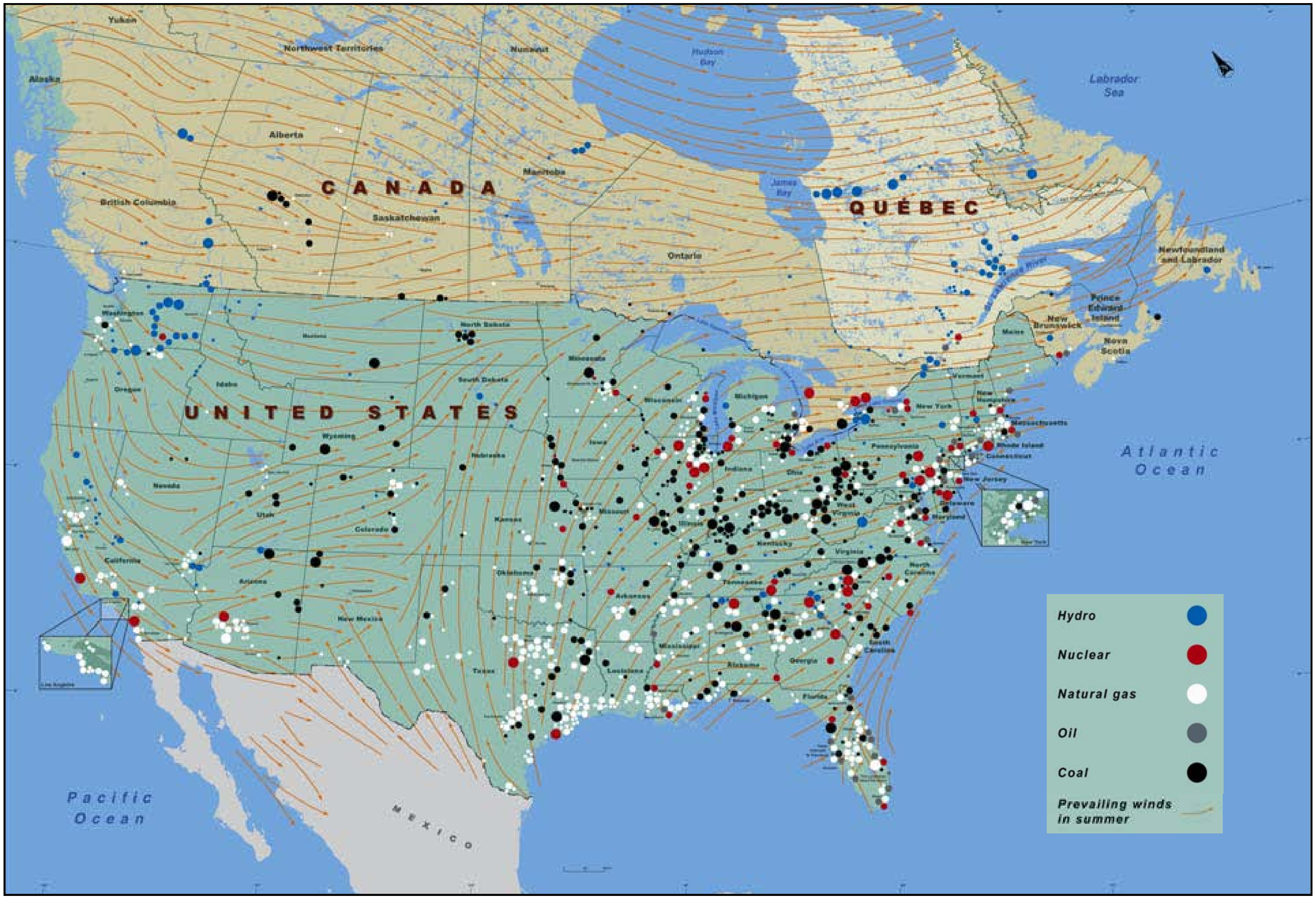
COMPARISON OF ELECTRIC GENERATION CAPACITY IN NORTH AMERICA (2006)



	United States	Canada	Québec
Installed capacity	1,076,000 MW	124,000 MW	40,000 MW
Electricity generation	4,064 TWh	592 TWh	180 TWh

Image by MIT OpenCourseWare. Source: Statistics Canada.

ELECTRICITY SUPPLY OPTIONS IN QUÉBEC AND THE REST OF NORTH AMERICA



Courtesy of Hydro-Québec. Used with permission.

TRANSMISSION SYSTEM

Neighboring system	Import mode (MW)	Export mode (MW)
New York	1,100	2,000
Ontario	1,945	2,705
New England	2,070	2,275
New-Brunswick	785	1,080
Newfoundland and Labrador	5,150	0

HYDROELECTRIC PROJECTS – 2005-2020

Map of projected Hydro-Quebec hydroelectric construction removed due to copyright restrictions. Please see this map of current Hydro-Quebec construction instead.

HYDRO POWER – SOME FACTS AND FIGURES, continued

- Big Range in Capacity and Size
  - Power capacity – 1 kWe to 14500 MWe
  - Hydraulic head < 1 m to 1500 m (from low-head to high-head) (S. Fiorano, Italy)
  - Largest earth dam height – 300 m (Tajikistan)
  - Largest reinforced concrete dam height– 305 m (China)
  - Reservoir volume – 180 km^3 (Zimbabwe)
  - Reservoir area – 8,482 km^2 (Lake Volta, Ghana)
- Theoretical Potential, Technically Exploitable –
  - 15000 TWh/yr or about 4,000,000 MWe of capacity

REPRESENTATIVE MEGA-SCALE HYDROPOWER PROJECTS

Name	Location	Type	Capacity, MWe	Reservoir size
Grand Coulee	Columbia River, Lake Roosevelt, Washington	Impoundment dam, 550 ft (170m) high	6809	9.6 million acre ft. 11.9 km^3
Niagara Falls	Niagara River. New York	Diversion, run of river	2400	nil
Hoover Dam	Colorado River, Lake Mead, Nevada	Impoundment dam, 726 ft (223m) high	2080	28.5 million acre ft. 35.2 km^3
Norris Dam TVA	Clinch River, Norris Lake, Tennessee	Impoundment dam, 265 ft (81m) high	131.4	
Glen Canyon	Colorado River, Lake Powell, Arizona	Impoundment dam, 710 ft (261m) high	1296	24.3 million acre ft. 30 km^3
James Bay Project La Grande 1, 2A, 3, 4 Robert-Bourassa Laforge 1, 2 Brisay Eastmain 1, 1A	La Grande River Watershed and Laforge River, Quebcc, Canada	Impoundment and run-of-river, multiple dams	 8671 +5616 +1197 + 469 + 768	>100 Quabbins!!
Itaipu	Parana River, Itaipu Lake, Paraguay/Brazil	Impoundment dam, 643 ft (196 m) high	14,000	23.5 x 10^{12} acre ft. 29 million km^3
Three Gorges	Yangze River, Three Gorges Lake China	Impoundment dam, 607 ft (185 m) high	18,200	31.8 million acre ft. 39.3 km^3
Guri	Caroni River, Venezuela	Impoundment dam, 531 ft (162 m) high	10,235	109.4 million acre ft. 135 km^3
Krasnoyarsk	Yenisey River, Krasnoyarsk Lake, Russia	Impoundment dam, 407 ft (124 m) high	6,000	59.4 million acre ft. 73.3 km^3

HYDROPOWER IS STRATEGICALLY IMPORTANT WORLDWIDE (2008)

- North America
  661,991 GWh/yr
- Central and South America
  665,316 GWh/yr
- Africa
  99,449 GWh/yr
- Asia and Oceania
  878,332 GWh/yr
- Europe
  547,732 GWh/yr
- Eurasia
  222,254 GWh/yr
- Middle East
  25,064 GWh/yr

1,560 North American Plants (5,000 Units)

13,000 International Plants (42,000 Units)

World Total = 3,100,139 GWh/yr

World Total = $50,000,000,000/yr

TEN OF THE LARGEST HYDROELECTRIC PRODUCERS (2009)

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of total capacity
China	585.2	196.79	0.37	22.25
Canada	369.5	88.974	0.59	61.12
Brazil	363.8	69.080	0.56	85.56
United States	250.6	79.511	0.42	5.74
Russia	167.0	45.000	0.42	17.64
Norway	140.5	27.528	0.49	98.25
India	115.6	33.600	0.43	15.80
Venezuela	86.8			67.17
Japan	69.2	27.229	0.37	7.21
Sweden	65.5	16.209	0.46	44.34

FUTURE HYDROELECTRIC PROJECTS OVER 5,000 MW

Name	Capacity (MW)	Country	Construction	Completion
Red Sea Dam	50,000	Djibouti Yemen	*Proposed*	
Grand Inga Dam	39,000	Congo DR	2014	2025
Three Gorges Dam	22,500	China	1994	2011
Baihetan Dam	13,050	China	2009	2015
Belo Monte Dam	11,233	Brazil	*Proposed*	
Wudongde Dam	7,500	China	2009	2015

Table 12.4 Potential for hydropower development in selected countries based on technical potential and economic potential in today's energy markets

Country	Hydro as % of total electricity	Ratio of theoretical potential to actual	Ratio of economic potential to actual
Norway	100	5.77	1.8
Brazil	91.7	5.4	3.0
Switzerland	80	–	1.1
Canada	63	3.81	1.54
India	25	4.2	3.0
France	20	1.15	1.0
China	17	10.1	6.6
Indonesia	14	31.3	3.13
United States	10	1.82	1.3
World total	**19**	**18.34**	**>2.78**

HYDROPOWER CAPACITY ESTIMATES

Continent	Capacity in 2005		Maximum Theoretical Potential	Technically Possible	Economically Possible
	GWe	TWh/yr	TWh/yr	TWh/yr	TWh/yr
Africa	21.6	83.7	3,884	1,852	> 200
North America	164.1	675.6	8,054	3,012	> 1,500
South America	123.7	596.5	7,121	3,036	> 2,000
Asia	222.7	718.2	16,285	5,523	> 2,500
Europe	225.2	705.5	4,945	2,714	> 1,000
Middle East	7.2	16.9	418	168	> 100
Oceania	13.5	40.4	495	189	> 100
Total World	**778.0**	**2,836.8**	**41,202**	**16,494**	

Source: World Energy Council

BASIC OPERATING EQUATIONS FOR HYDROPOWER

Total power from hydropower including both static (PE) and dynamic (KE) contribution

$$Power = (total\ \ hydrualic\ \ head) \times (volumetric\ flow\,rate) \times (efficiency)$$

$$Power\ \ = (\rho g Z + 1/2\rho\Delta(v^2)) \times Q \times \varepsilon$$

For impoundment hydro systems with only static hydraulic head (PE) recovered and no recovery of flowing head (KE)

$$Power = 9.81 \times 10^3 ZQ\varepsilon\ \ in\,watts = 9.81 \times 10^{-3} ZQ\varepsilon\ \ \ in\,\mathrm{MWe}$$

TURBINE TYPES

- Impulse Turbine
  - Pelton
    - Turgo Wheel
  - Cross-Flow
- Reaction Turbine
  - Propeller
    - Bulb
    - Straflo
    - Tube
    - Kaplan
  - Francis
  - Kinetic

Images of turbines removed due to copyright restrictions.
Please see "Types of Hydropower Turbines."
U.S. Department of Energy, Energy Efficiency & Renewable Energy.
Also see Turgo, Cross-Flow, Straflo, and Kinetic turbines.

http://www1.eere.energy.gov/water/hydro_turbine_types.html

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1,560 North American Plants (5,000 Units)

13,000 International Plants (42,000 Units)

World Total = 3,100,139 GWh/yr

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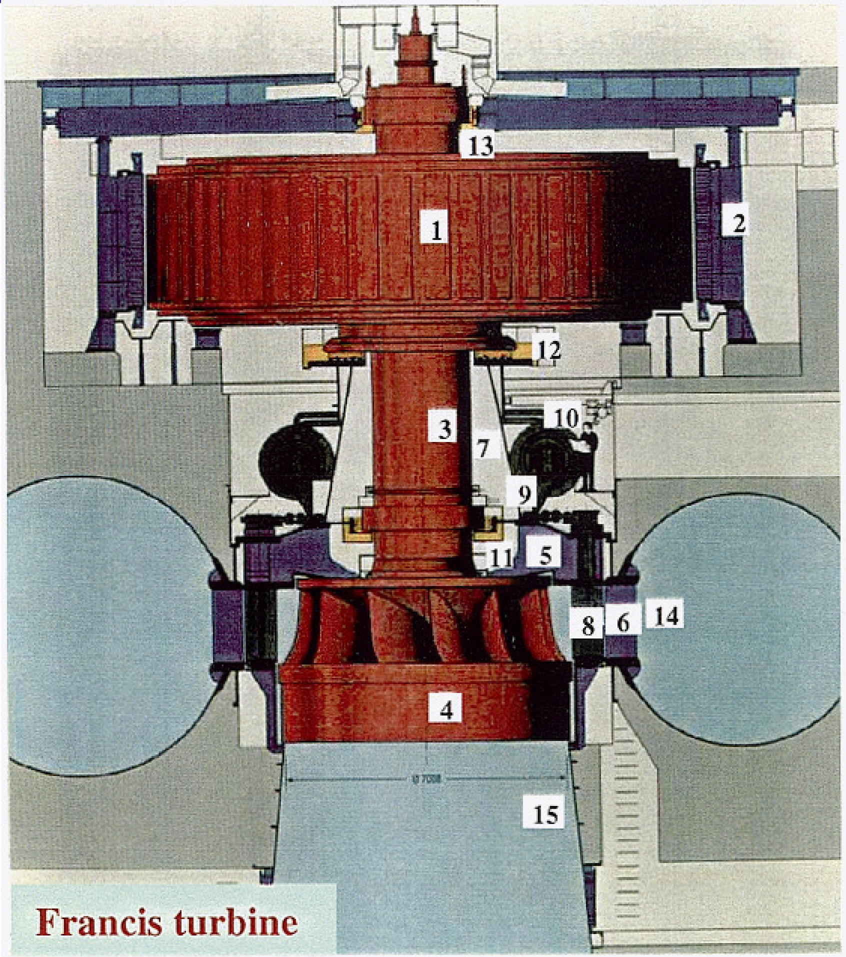
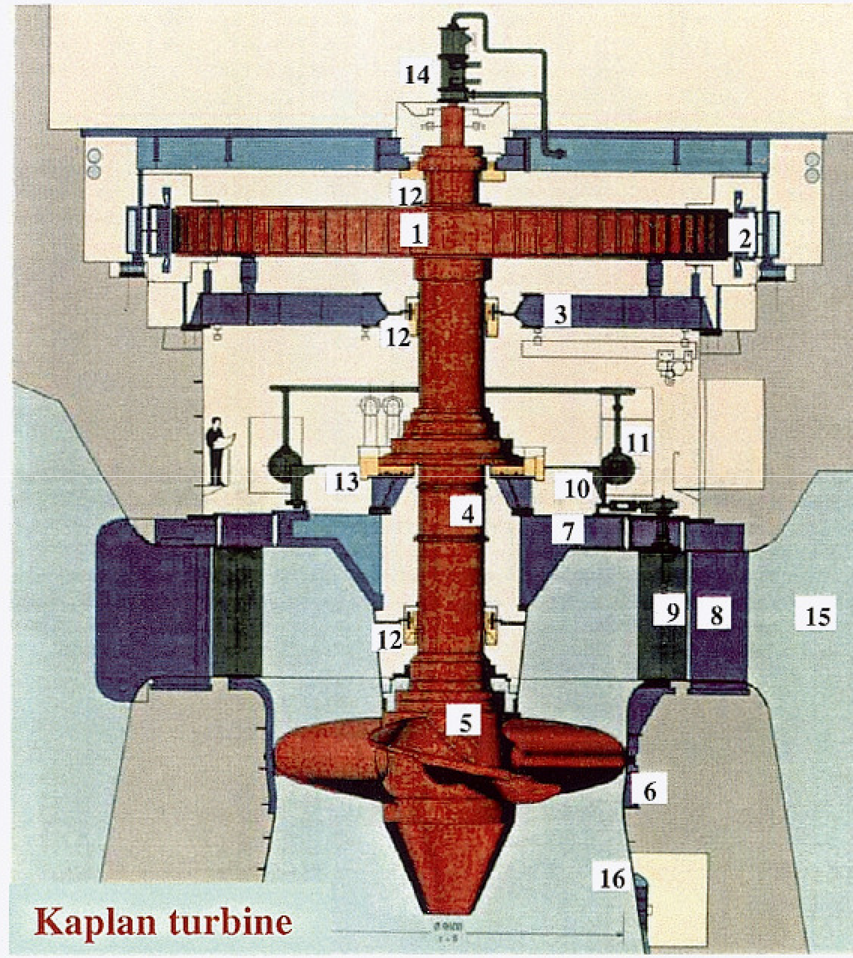
FRANCIS AND KAPLAN TURBINES



Francis turbine

1. Generator Rotor
2. Generator Stator
3. Turbine Shaft
4. Runner
5. Turbine Head Cover
6. Stay Ring Discharge Ring
7. Supporting Cone
8. Guide Vane
9. Operating Ring
10. Guide Vane Servomotor
11. Lower Guide Bearing
12. Thrust Bearing
13. Upper Guide Bearing
14. Spiral Case
15. Draft Tube Cone



Kaplan turbine

1. Generator Rotor
2. Generator Stator
3. Spider
4. Turbine Shaft
5. Runner
6. Discharge Ring
7. Turbine Cover
8. Stay Ring
9. Guide Vane
10. Operating Ring
11. Guide Vane Servomotor
12. Guide Bearing
13. Thrust Bearing
14. Oil Supply Head
15. Concrete Semi-spiral Case
16. Draft Tube Cone

Franke, Gary F,. et al. "Development of Environmentally Advanced Hydropower Turbine System Design Concepts." U.S. Department of Energy, Idaho National Engineering Laboratory (August 1997): INEEL/EXT-97-00639. http://dx.doi.org/10.2172/563213

HYDRAULIC TURBINES: DOMAINS OF HEAD AND SCALE IN THE ENGINEERING PRACTICE OF PELTON, FRANCIS AND KAPLAN TURBINES

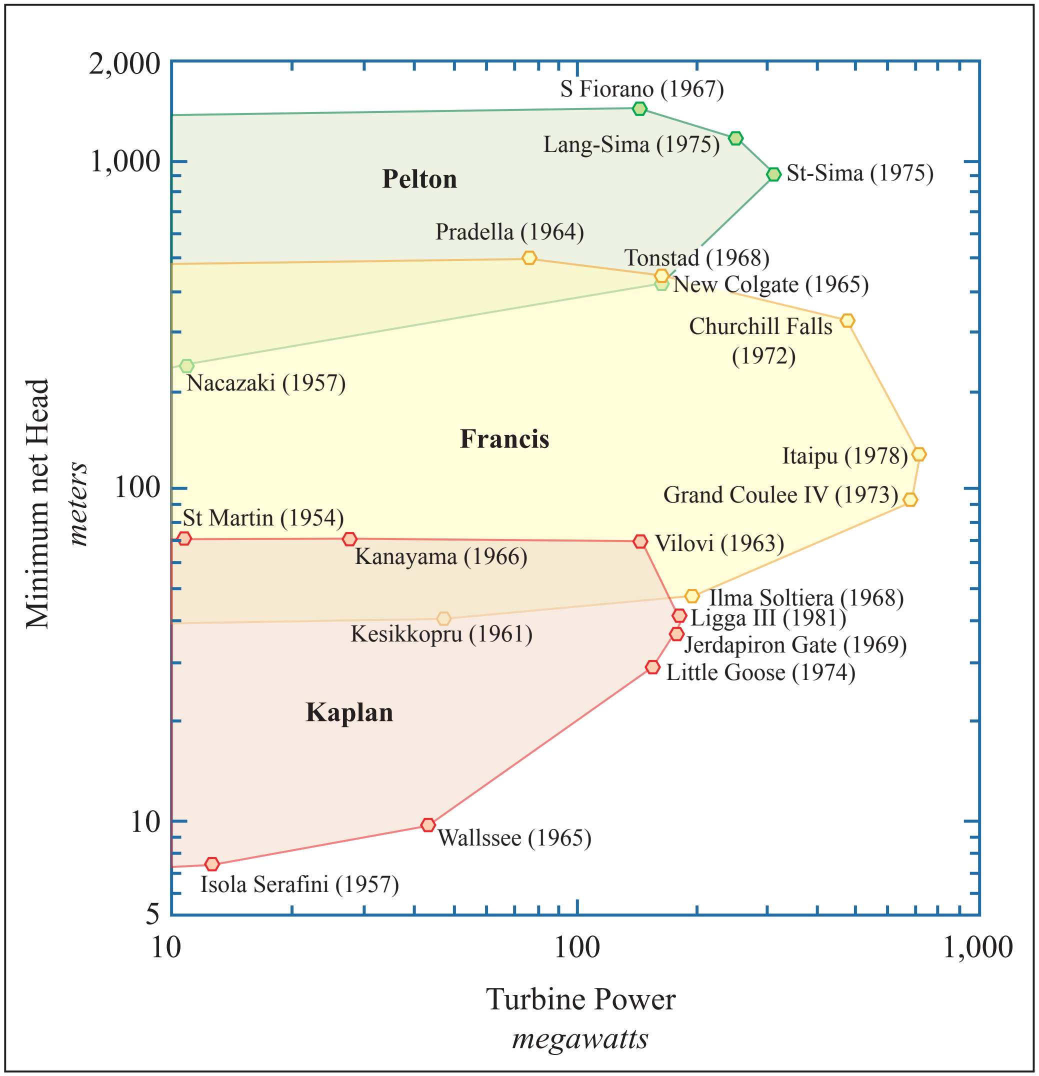


Image by MIT OpenCourseWare.

MAJOR ATTRIBUTES OF HYDROPOWER

Positive	Negative
Emissions-free, with virtually no CO_2, NO_x, SO_x, hydrocarbons, or particulates	Frequently involves impoundment of large amounts of water with loss of habitat due to land inundation
Renewable resource with high conversion efficiency to electricity (80%)	Variable output - dependent on rainfall and snowfall
Dispatchable with storage capability	Impacts on river flows and aquatic ecology, including fish migration and oxygen depletion
Usable for base load, peaking, and pumped storage applications	Social impacts of displacing indigenous people
Scalable from 10 kWe to 10,000 MWe	Health impact in developing countries
Low operating and maintenance cost	High initial capital costs
Long lifetime - 50 years typical	Long lead time in construction in mega-sized projects

HYDRO POWER – ECONOMIC ISSUES

- Very capital intensive include "fuel costs"
- Large projects > 100 MWe have long lead times (4-6 yr)
- Long lifetimes and low operating and maintenance costs
- Large seasonal variation [factors of 2 to 10 in flow common]
- Costs very sensitive to natural terrain and climate e.g., compare Switzerland's mountainous relief and high rainfall to the flatter, dryer Midwestern regions of the US
- Installed costs range from about $750/kW to $2000/kW for 10-1000 MWe plants
- With intrinsic output variability need to inflate costs- typically range from $1500 to 6000 per reliable kilowatt

HYDRO POWER – ENVIRONMENTAL AND SOCIAL ISSUES

- Land Use – Inundation and Displacement of People
- Impacts on Natural Hydrology
  - Infiltration
  - Increase evaporative losses
  - Altering river flows and natural flooding cycles
  - Sedimentation/silting
- Water Chemistry Changes
  - Mercury, nitrates, oxygen
  - Bacterial and viral infections (maleria, schitosomiasis, cholera,…)

EFFECTS OF HYDROELECTRIC FACILITIES

- Biological Effects
  - Change in aquatic ecosystem – species change
  - Damage to organisms passing through turbine
  - Oxygen depletion downstream of dams
  - Blockage of migration/breeding paths
  - Parasite growth

EFFECTS OF HYDROELECTRIC FACILITIES, cont’

- Physical Effects
  - Interruption of flooding cycles (silt, flood, transport)
  - Increased temperature
  - Increased evaporation
  - Increased leakage
  - Silting
  - Earthquakes
  - Dam failures and overtopping

SYMMARY – HYDROPOWER

- Is Simple, Ancient Technology
- Is the Most Important Industrial-Scale Renewable Energy Technology
- Is Largely Opposed by “Green” Lobbies
  - Opposition to new dams
  - Decommissioning of existing dams
- Disruptive Ecological and Hydraulically
- Catastrophic Failures are Possible

ARCHIVAL WEB SITES ON HYDROPOWER

- http://www.eere.energy.gov/basics/renewable_energy/hydropower.html
- http://www.worldenergy.org/
- http://hydropower.inel.gov/
- http://hydro.org/why-hydro/
- http://www.energy.ca.gov/hydroelectric/index.html
- http://www.unep.org/dams/WCD/
- http://www.ussdams.org