Hydropower

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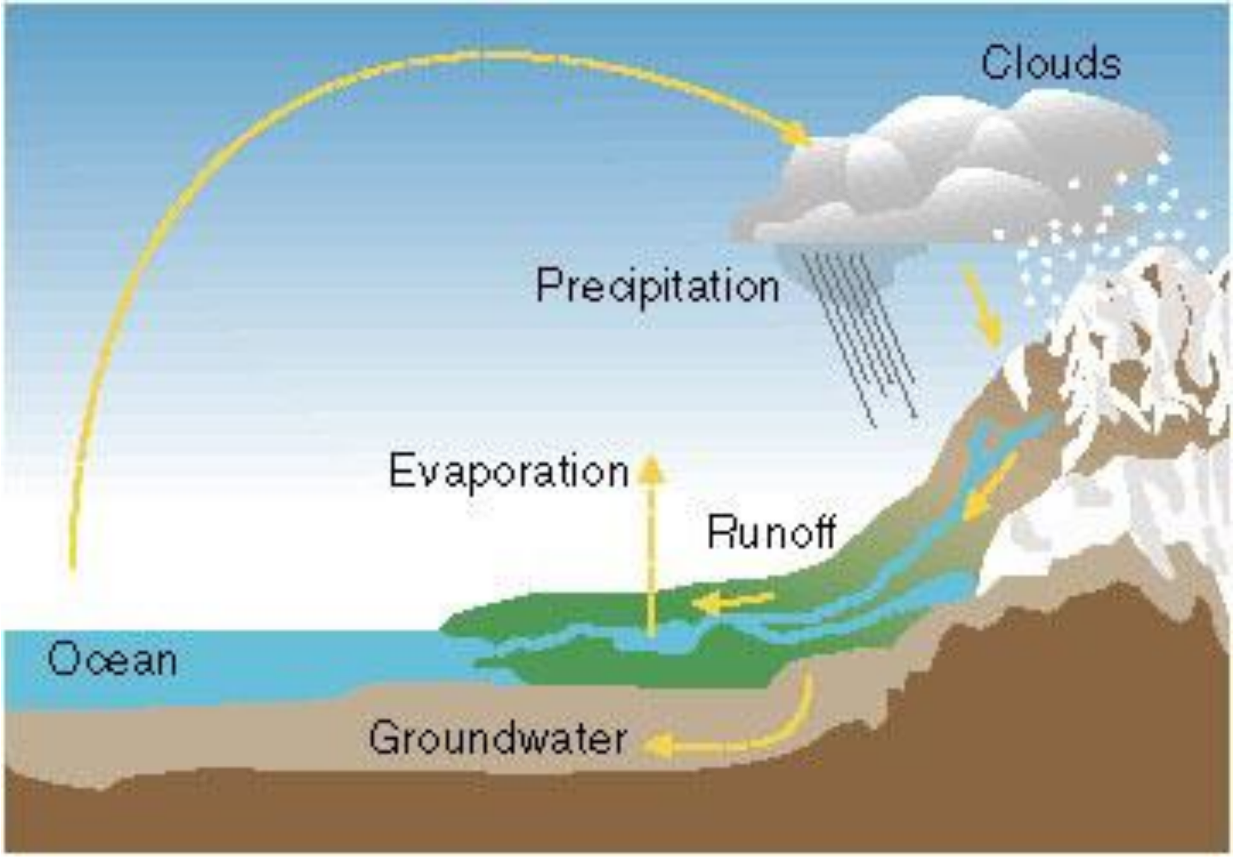
Most of the material of this lecture is from Prof. S. Lawrence,
Leeds School of Business, University of Colorado, Boulder, CO

Course Outline

- Renewable
  - **Hydro Power**
  - Wind Energy
  - Oceanic Energy
  - Solar Power
  - Geothermal
  - Biomass
- Sustainable
  - Hydrogen & Fuel Cells
  - Nuclear
  - Fossil Fuel Innovation
  - Exotic Technologies
  - Integration
    - Distributed Generation

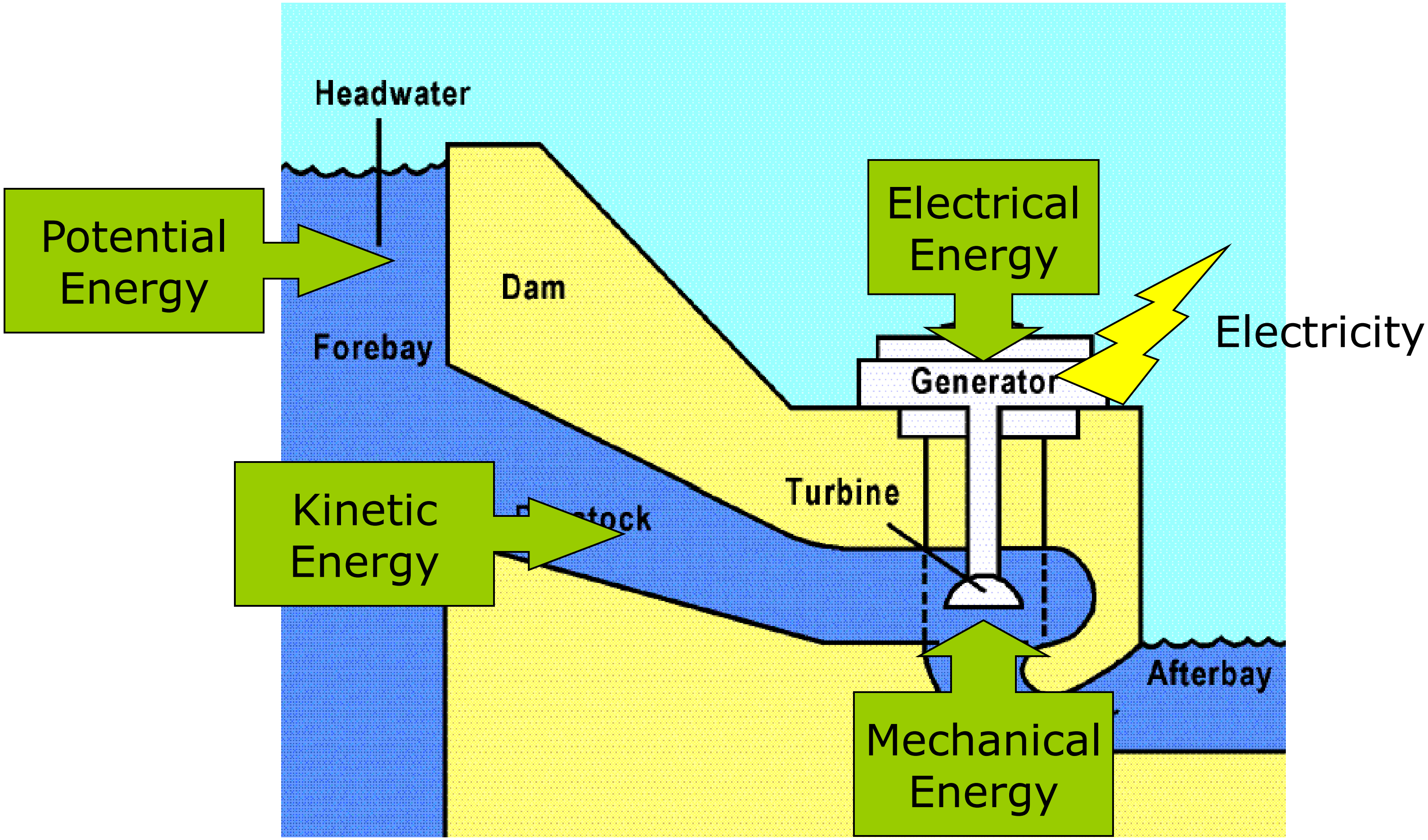
Hydro Energy

Hydrologic Cycle



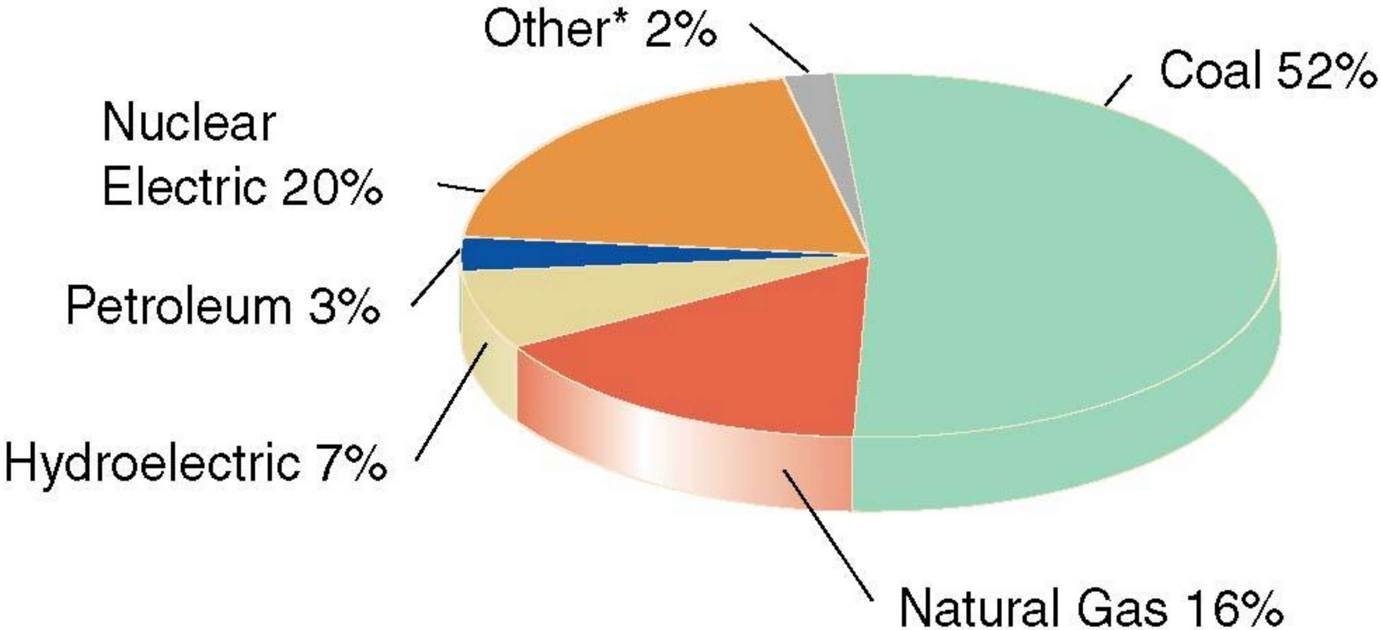
http://www1.eere.energy.gov/windandhydro/hydro_how.html

Hydropower to Electric Power



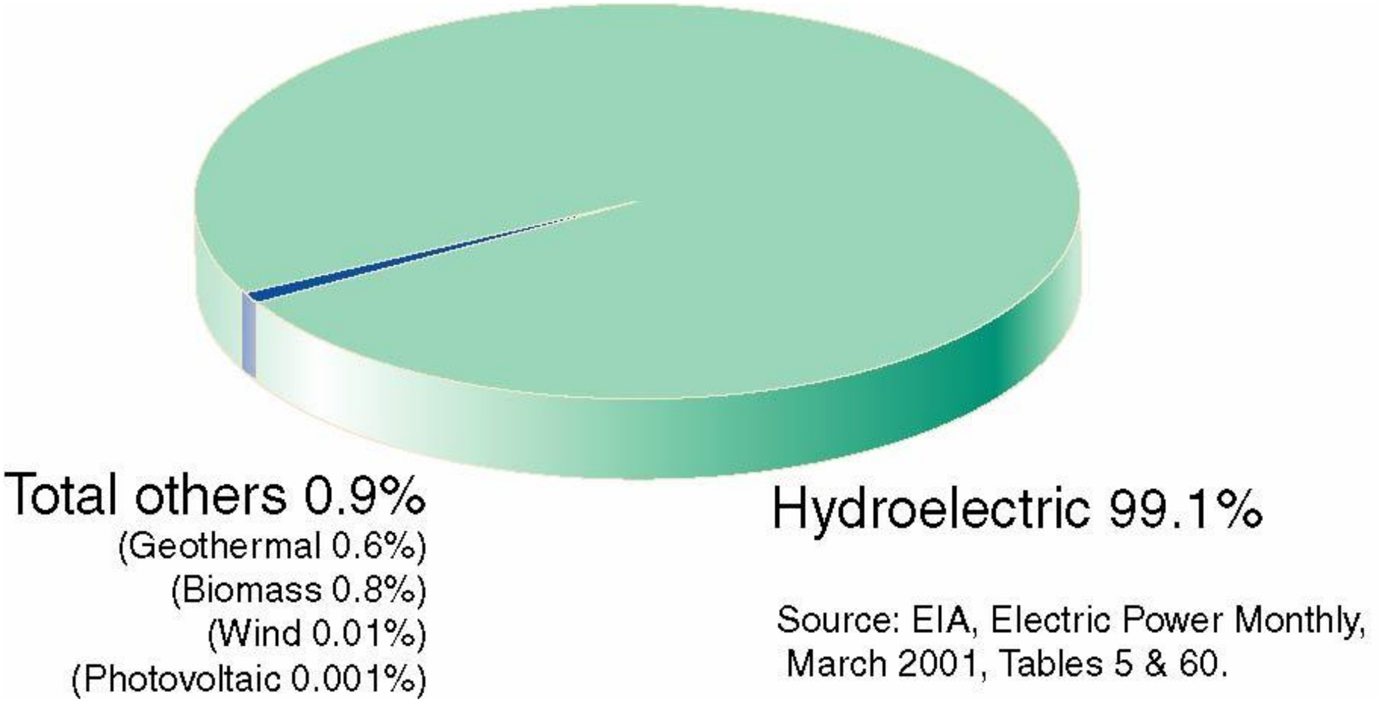
Hydropower in Context

Sources of Electric Power – US



Source: EIA, Electric Power Monthly, March 2001. Tables 3 & 58.
* Other includes geothermal, biomass, wind, photovoltaic, and solar thermal.
Includes utility and nonutility generation.

Renewable Energy Sources



Wisconsin Valley Improvement Company, http://www.wvic.com/hydro-facts.htm

World Trends in Hydropower

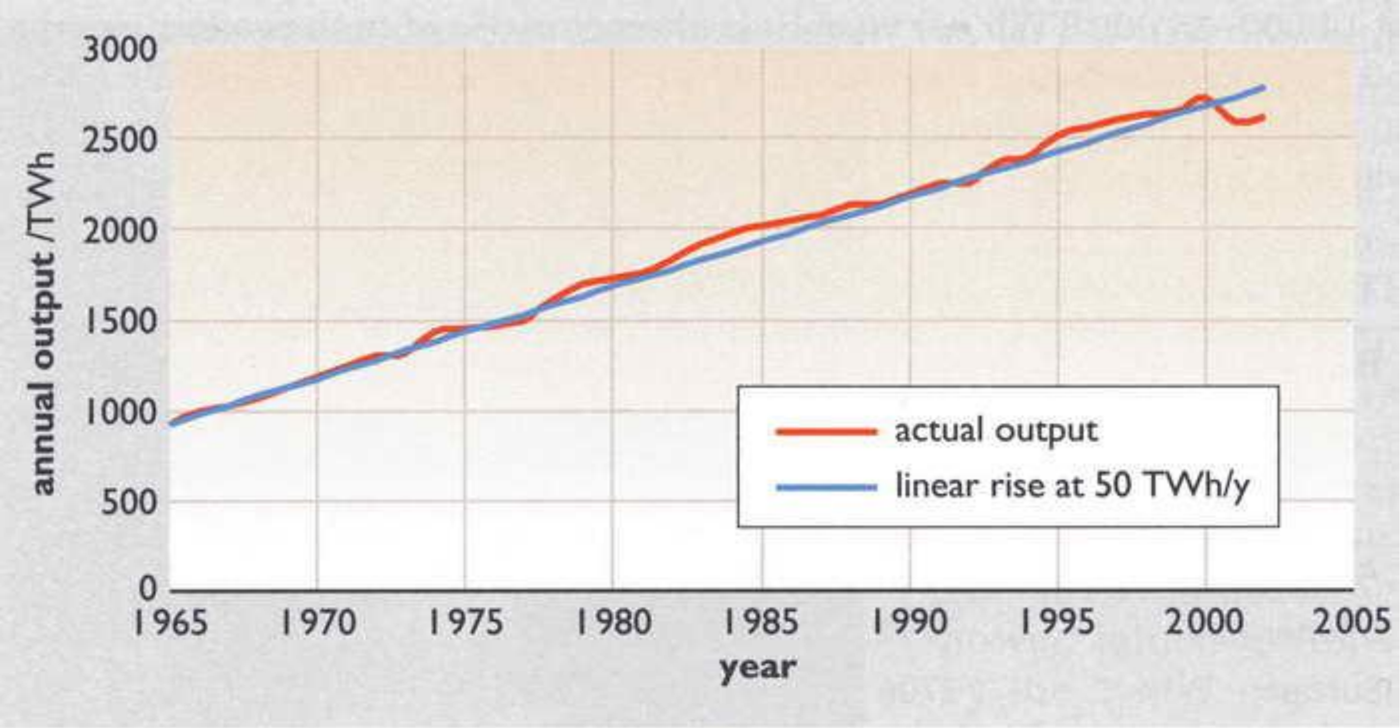


Figure 5.4 World annual hydroelectricity output, 1965–2002 (source: BP, 2003)

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

World hydro production

Producers	TWh	% of World total
Canada	338	12.4
Brazil	306	11.2
United States	306	11.2
People's Rep. of China	284	10.4
Russia	158	5.8
Norway	106	3.9
Japan	104	3.8
India	75	2.8
France	64	2.3
Venezuela	61	2.2
Rest of the World	924	34.0
World	**2 726**	**100.0**

2003 data

Installed Capacity (based on production)	GW
United States	94
Canada	69
Brazil	65
People's Rep. of China	58
Japan	46
Russia	44
Norway	28
India	27
France	25
Venezuela	13
Rest of the World	307
World	**776**

2002 data
Sources: United Nations, IEA.

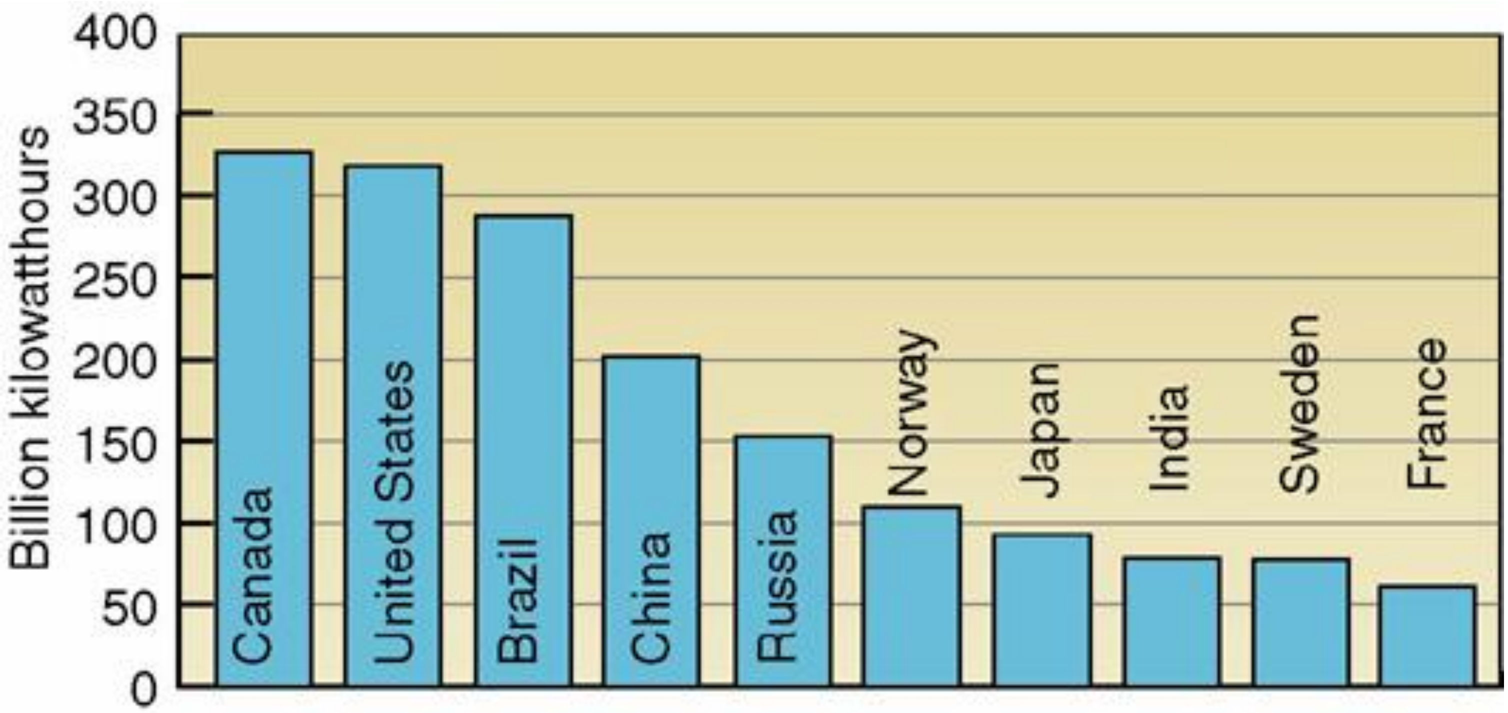
Country (based on first 10 producers)	% of hydro in total domestic electricity generation
Norway	98.9
Brazil	83.8
Venezuela	66.0
Canada	57.5
Russia	17.2
People's Rep. of China	14.9
India	11.9
France	11.4
Japan	9.9
United States	7.5
Rest of the World*	15.2
World	**16.3**

2003 data

** Excludes countries with no hydro production.*

IEA.org

Major Hydropower Producers



Source: EIA, Annual Energy Review 1999, July 2000, Table 11.15

World’s Largest Dams

Name	Country	Year	Max Generation	Annual Production
Three Gorges	China	2009	18,200 MW	
Itaipú	Brazil/Paraguay	1983	12,600 MW	93.4 TW-hrs
Guri	Venezuela	1986	10,200 MW	46 TW-hrs
Grand Coulee	United States	1942/80	6,809 MW	22.6 TW-hrs
Sayano Shushenskaya	Russia	1983	6,400 MW	
Robert-Bourassa	Canada	1981	5,616 MW	
Churchill Falls	Canada	1971	5,429 MW	35 TW-hrs
Iron Gates	Romania/Serbia	1970	2,280 MW	11.3 TW-hrs
Aswan Dam	Egypt	1950	2,100 MW	

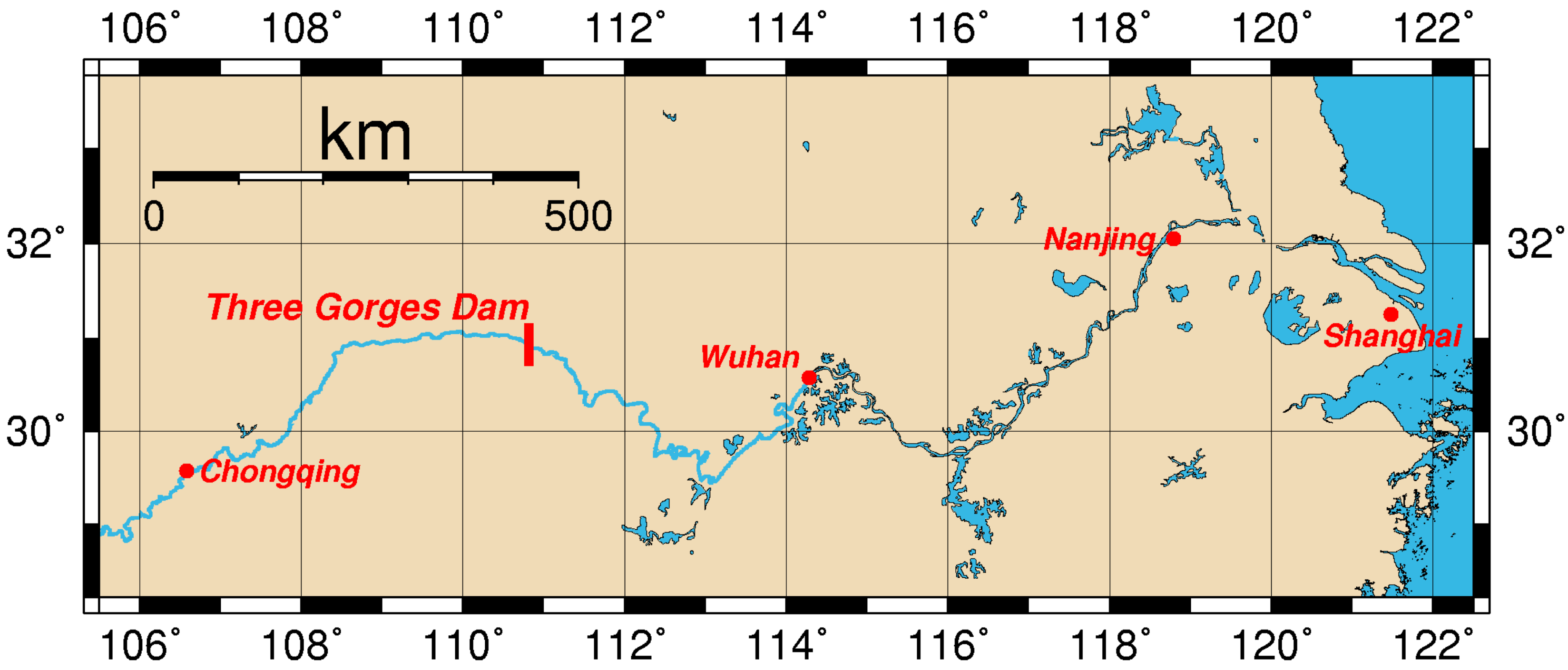
Ranked by maximum power.

The Electricity production from hydroelectric sources in Egypt was 12.863 (TWh) in 2009, according to a World Bank report, published in 2010.

“Hydroelectricity,” Wikipedia.org

Three Gorges Dam (China) 18GW

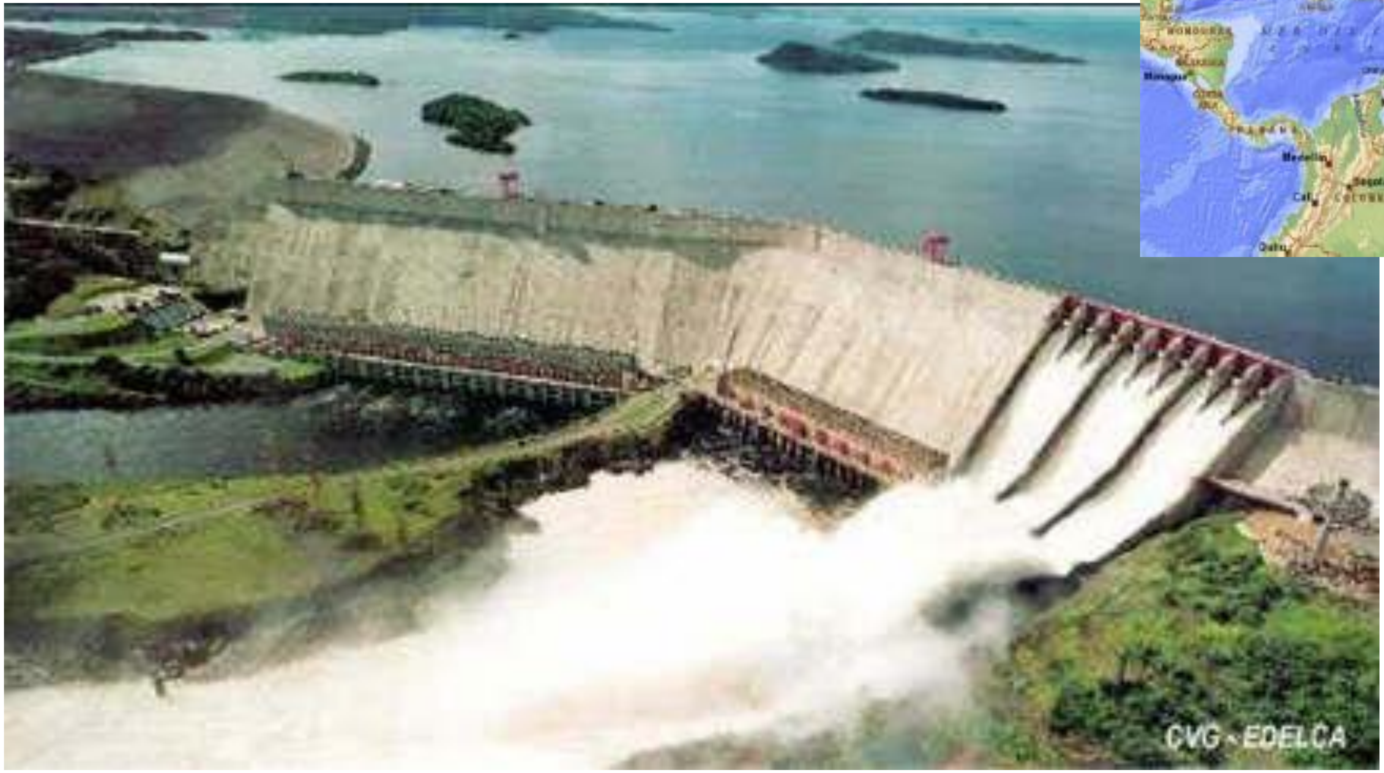
Three Gorges Dam Location Map



Itaipú Dam (Brazil & Paraguay) 12GW

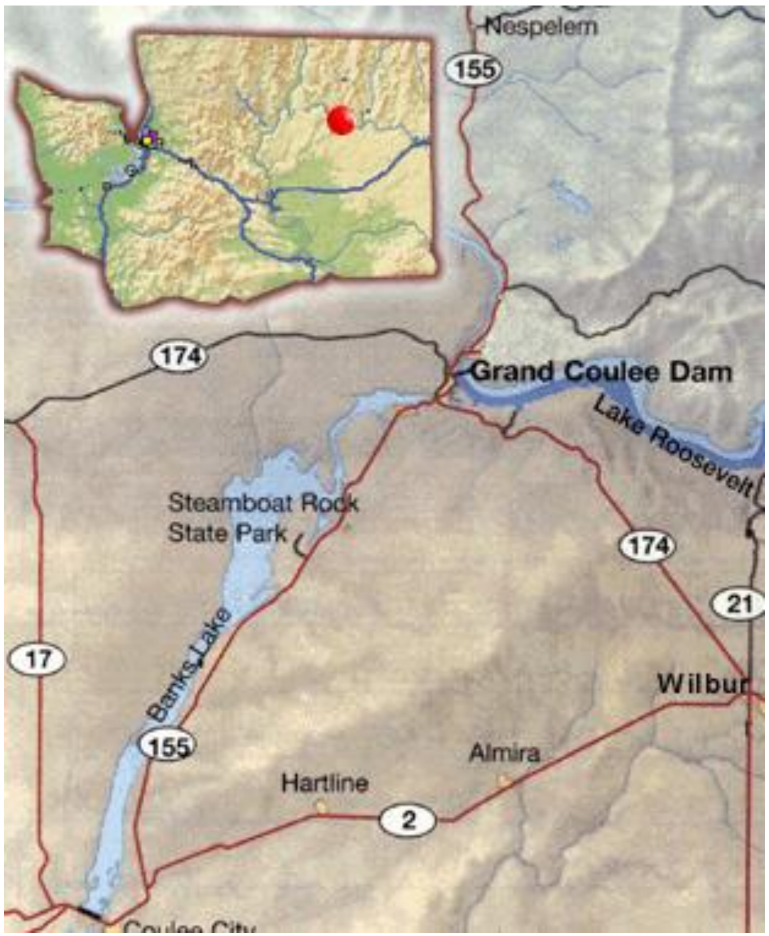
“Itaipu,” Wikipedia.org

Guri Dam (Venezuela) 10GW



http://www.infodestinations.com/venezuela/espanol/puerto_ordaz/index.shtml

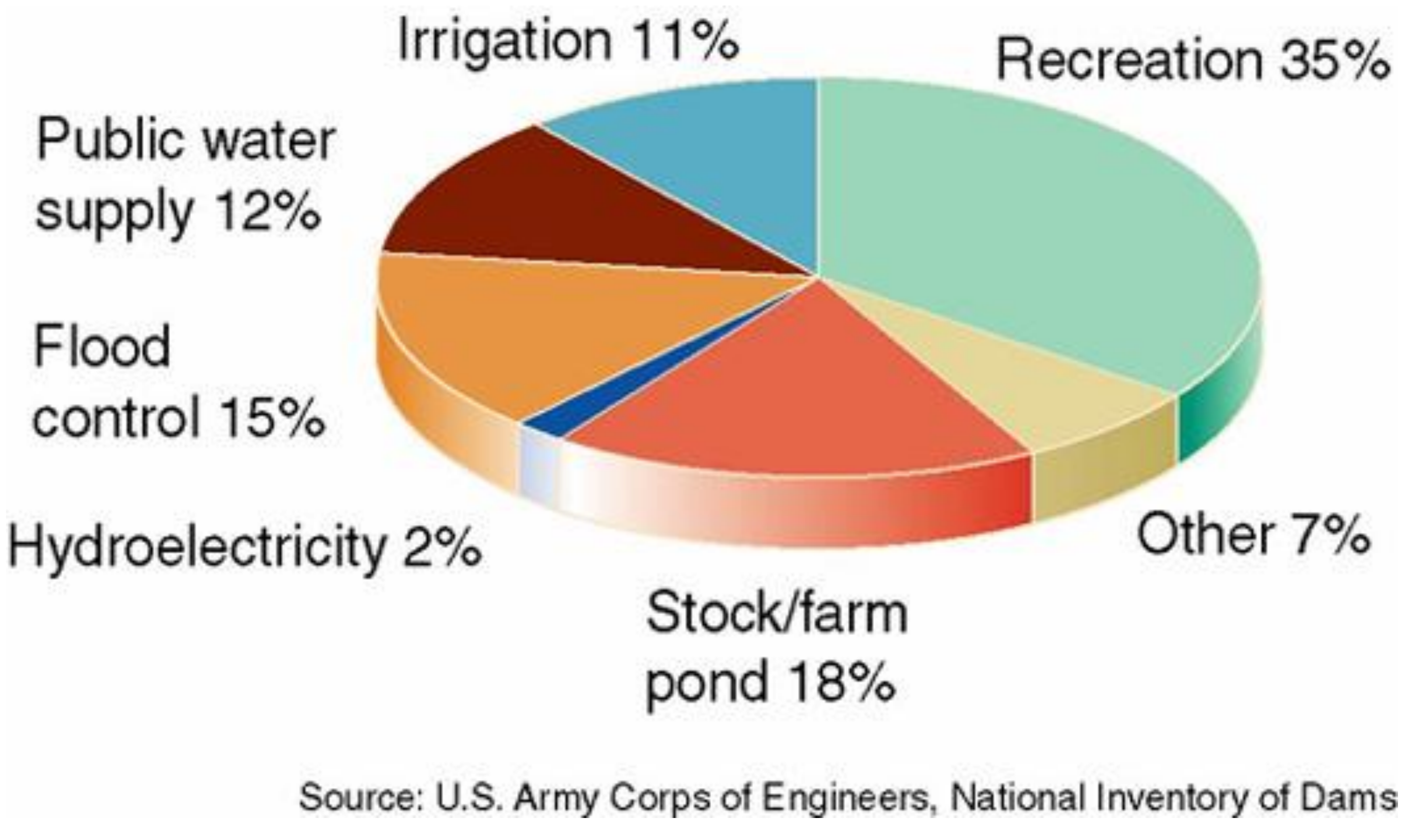
Grand Coulee Dam (US) 7GW



Located in Washington

www.swehs.co.uk/ docs/coulee.html

Uses of Dams – US



Wisconsin Valley Improvement Company, http://www.wvic.com/hydro-facts.htm

History of Hydro Power

Early Irrigation Waterwheel

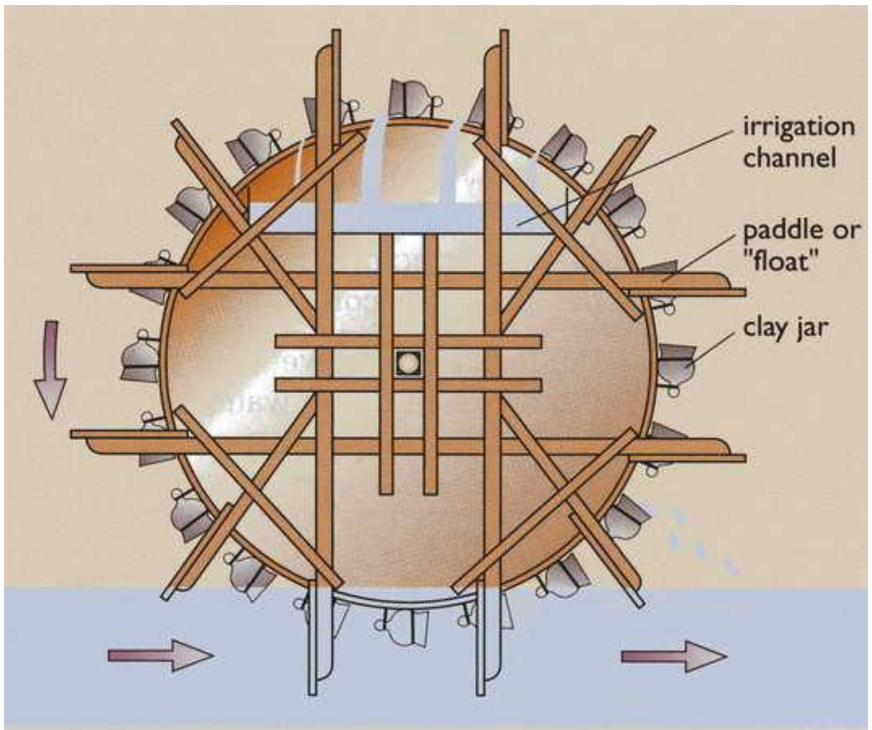


Figure 5.5 A noria. In this earliest water-wheel the paddles dip into the flowing stream and the rotating wheel lifts a series of jars, raising water for irrigation

A **noria** (Arabic: ناعورة, *nāʿūra*)

The norias of Hama on the Orontes River in Syria
Orontes river: نهر العاصي

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Early Roman Water Mill

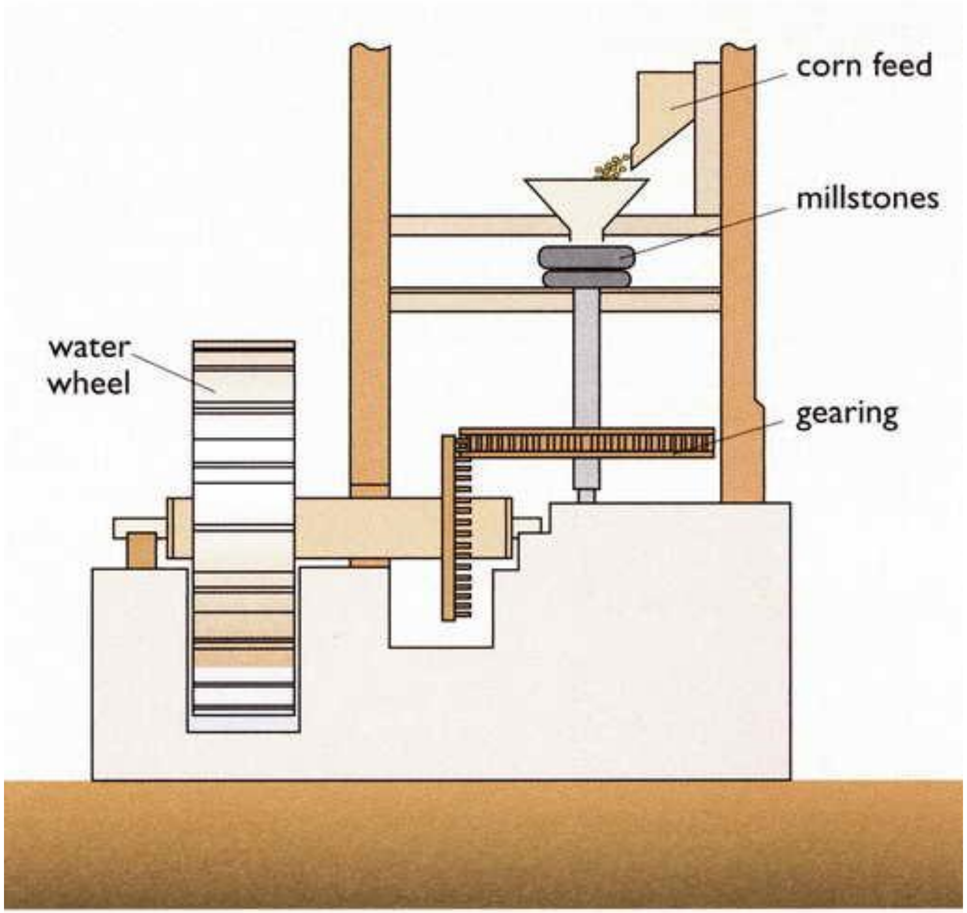


Figure 5.7 A Roman mill. This corn mill with its horizontal-axis wheel was described by Vitruvius in the first century BC. Note the use of gears

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

Early Norse Water Mill

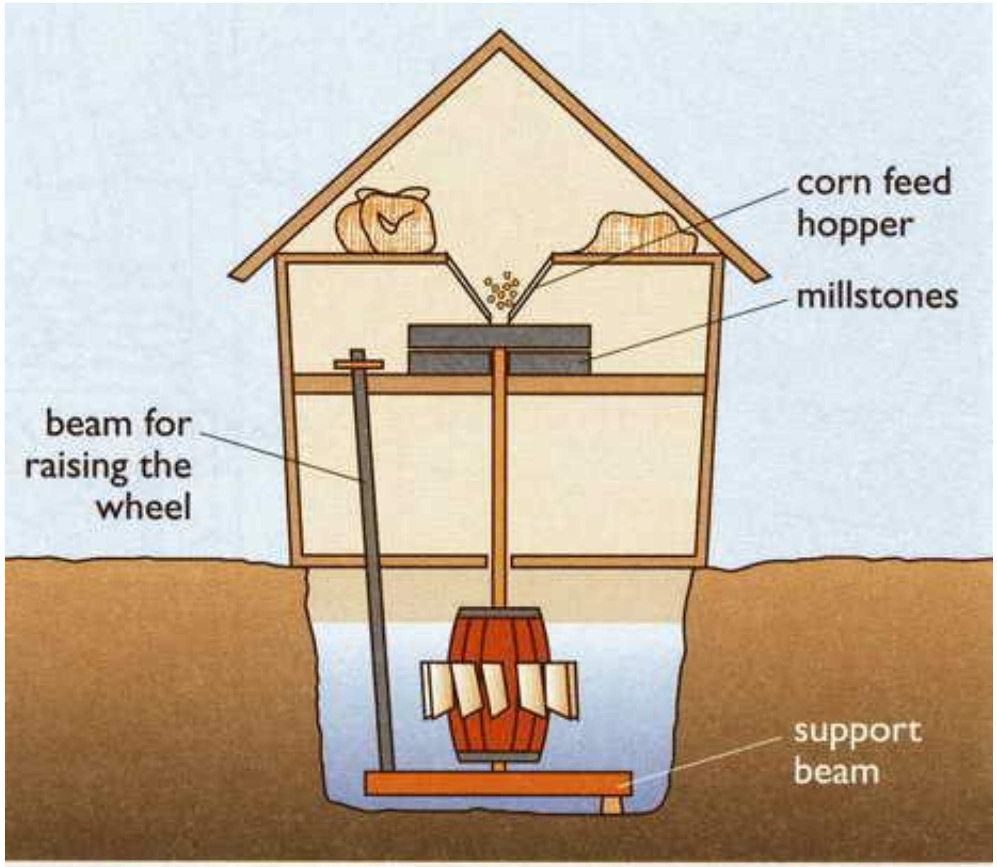


Figure 5.6 A Norse mill. Mills of this early vertical-axis type are still in use for mechanical power in remote mountainous regions

Norse mill: مطحنة الإسكندنافيةآ

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Fourneyron's Turbine

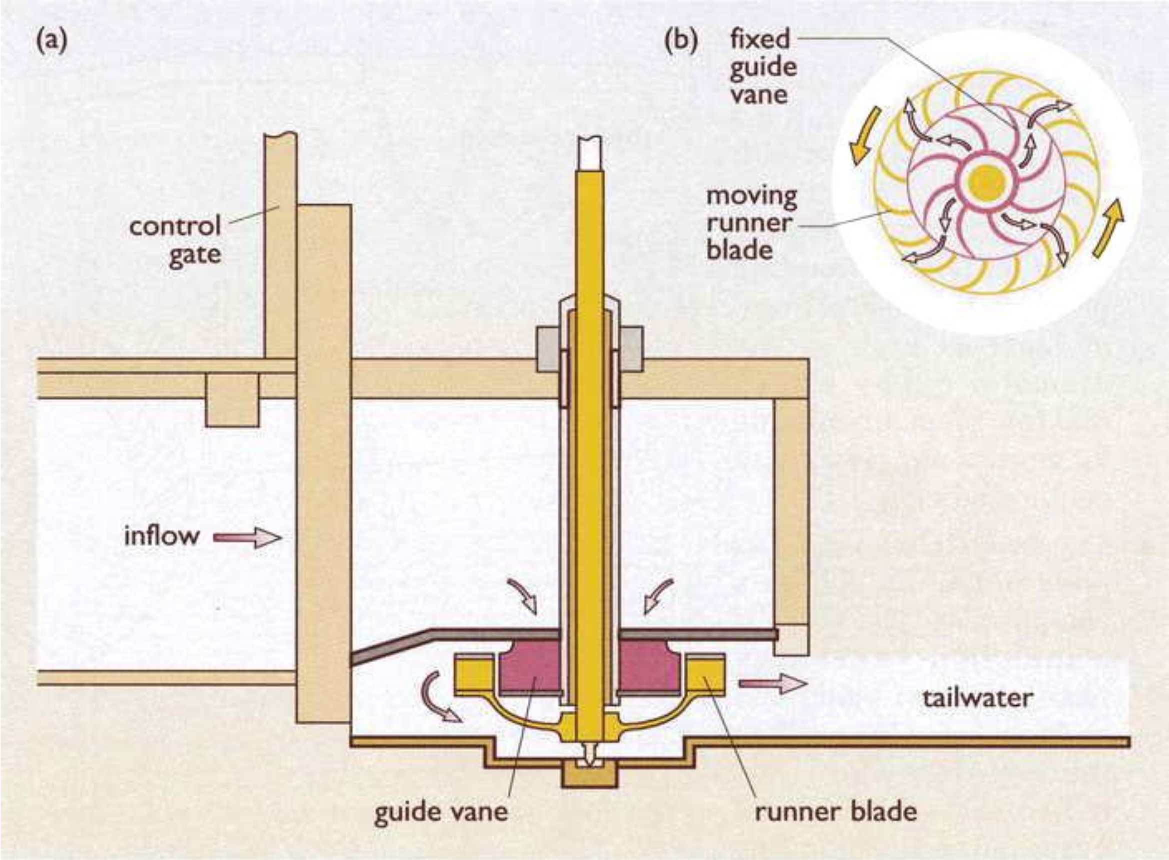


Figure 5.10 Fourneyron's turbine. The runner consists of a circular plate with curved blades around its rim and a central shaft. It spins under the force exerted by water flowing outwards between the fixed guide vanes and across its blades: (a) vertical section; (b) flow across guide vanes and runner

Benoît Fourneyron (1802 – 1867) was a French engineer, born in Saint-Étienne, Loire. Fourneyron made significant contributions to the development of water turbines.

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Hydropower Design

Terminology

- 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** (270 or more meters)
  - **medium-head** (30 to 270 m)
  - **low-head** (less than 30 m)
- Power is proportional to the product of

  head x flow

http://www.wapa.gov/crsp/info/harhydro.htm

Scale of Hydropower Projects

- Large-hydro
  - More than 100 MW feeding into a large electricity grid
- Medium-hydro
  - 15 - 100 MW usually feeding a grid
- Small-hydro
  - 1 - 15 MW - usually feeding into a grid
- Mini-hydro
  - Above 100 kW, but below 1 MW
  - Either stand alone schemes or more often feeding into the grid
- Micro-hydro
  - From 5kW up to 100 kW
  - Usually provided power for a small community or rural industry in remote areas away from the grid.
- Pico-hydro
  - From a few hundred watts up to 5kW
  - Remote areas away from the grid.

www.itdg.org/docs/technical_information_service/micro_hydro_power.pdf

Types of Hydroelectric Installation

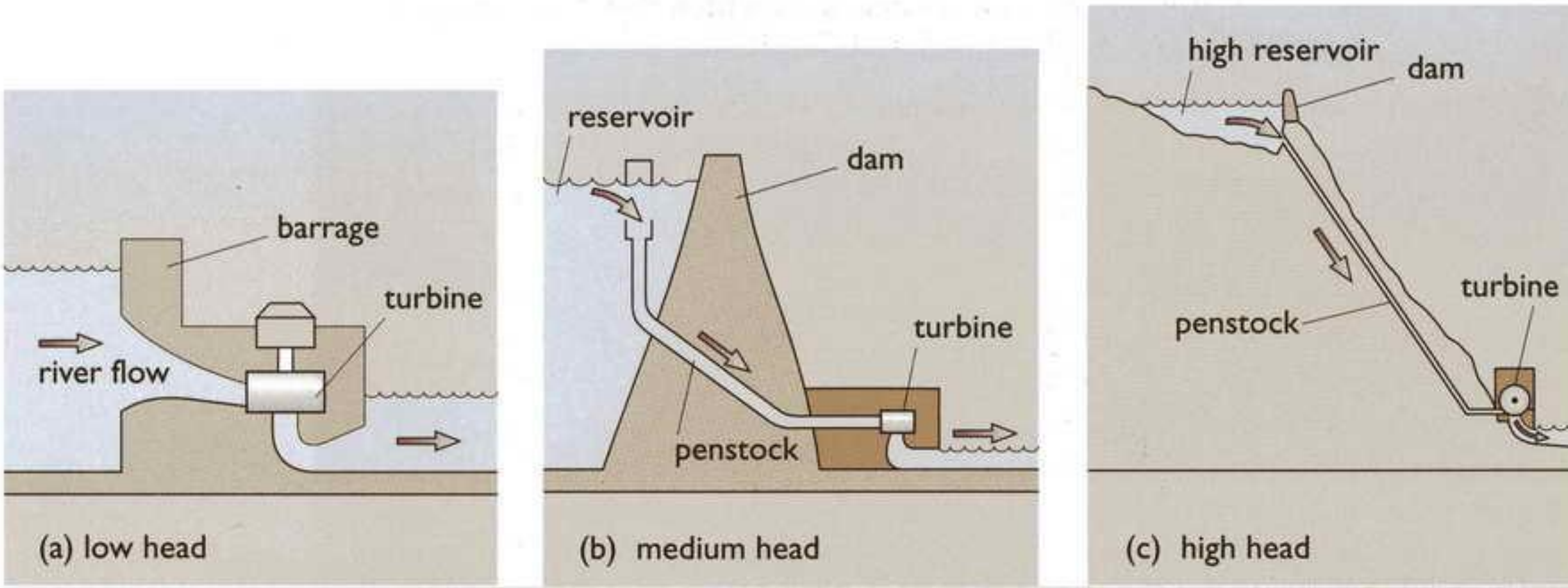


Figure 5.13 Types of hydroelectric installation

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

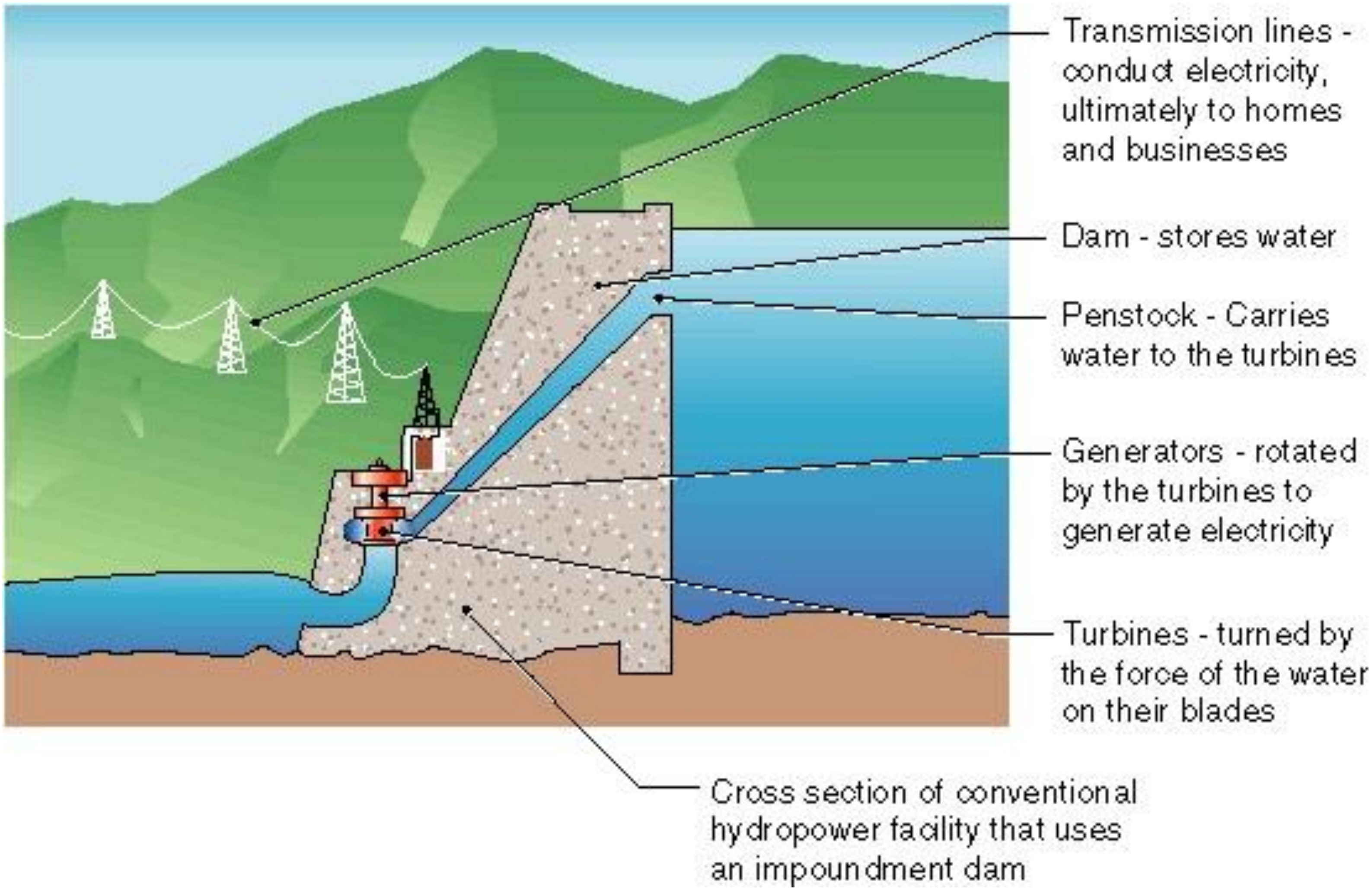
Meeting Peak Demands

- Hydroelectric plants:
  - Start easily and quickly and change power output rapidly.
  - Complement large thermal plants (coal and nuclear), which are most efficient in serving base power loads.
  - Save millions of barrels of oil.

Types of Systems

- Impoundment محجوزة
  - Hoover Dam, Grand Coulee
- Diversion or run-of-river systems
  - Niagara Falls
  - Most significantly smaller
- Pumped Storage
  - Two way flow
  - Pumped up to a storage reservoir and returned to a lower elevation for power generation
    - A mechanism for energy storage, not net energy production

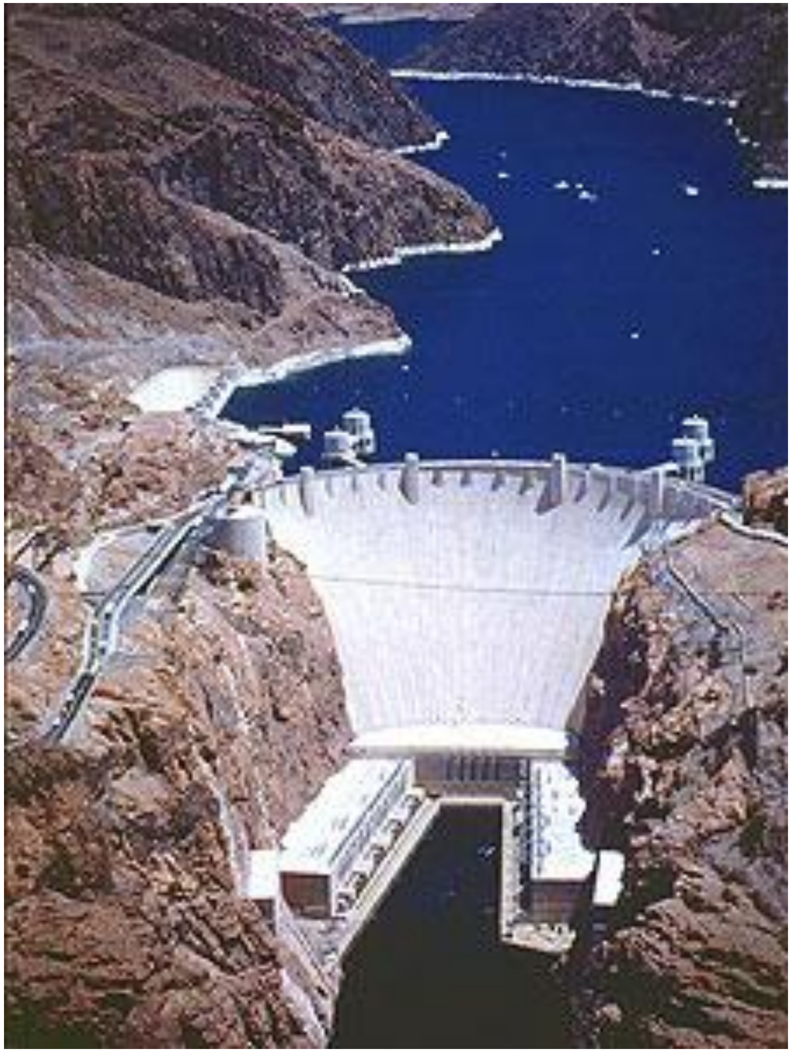
Conventional Impoundment Dam



http://www1.eere.energy.gov/windandhydro/hydro_plant_types.html

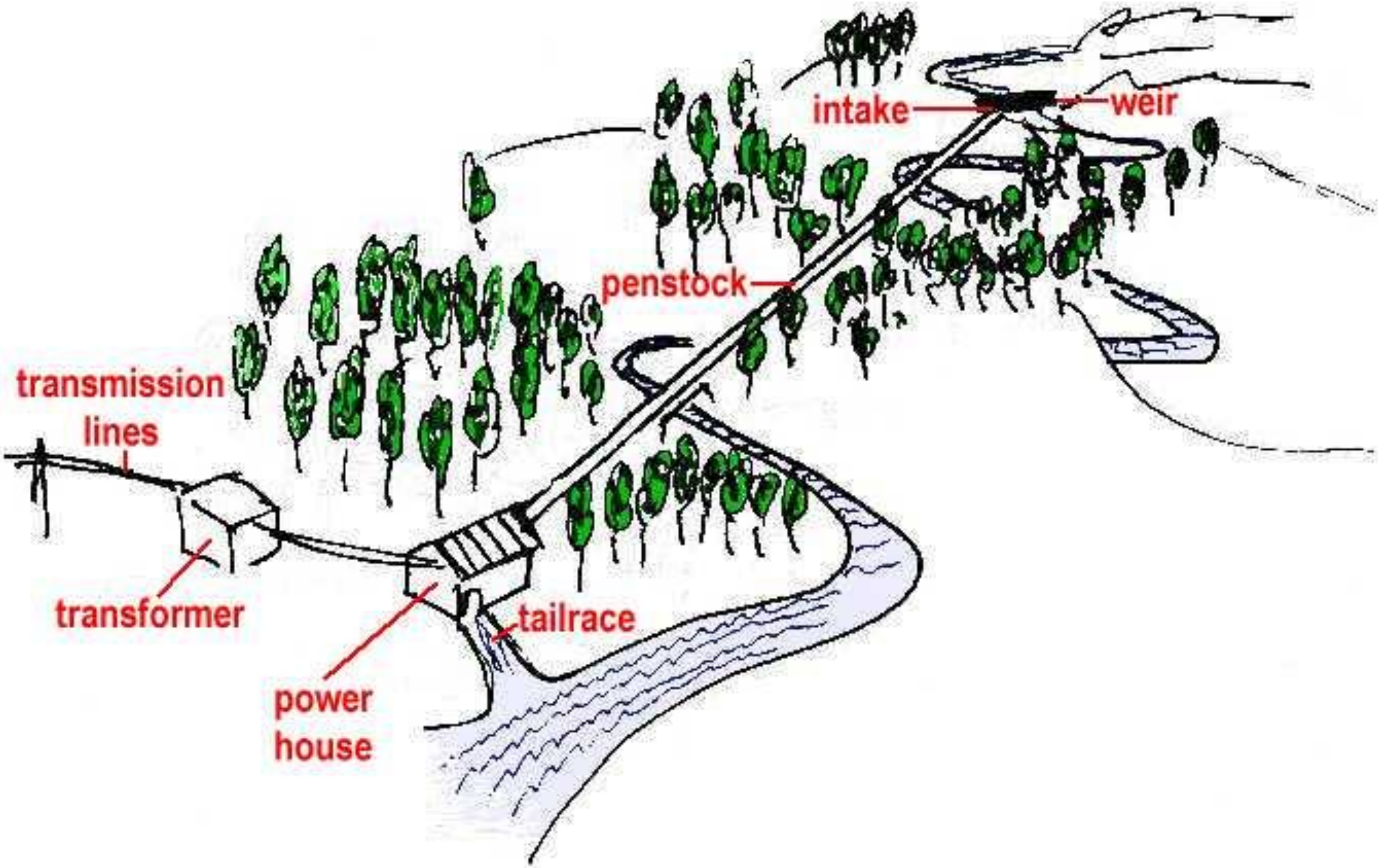
Example

Hoover Dam (US)



http://las-vegas.travelnice.com/dbi/hooverdam-225x300.jpg

Diversion (Run-of-River) Hydropower

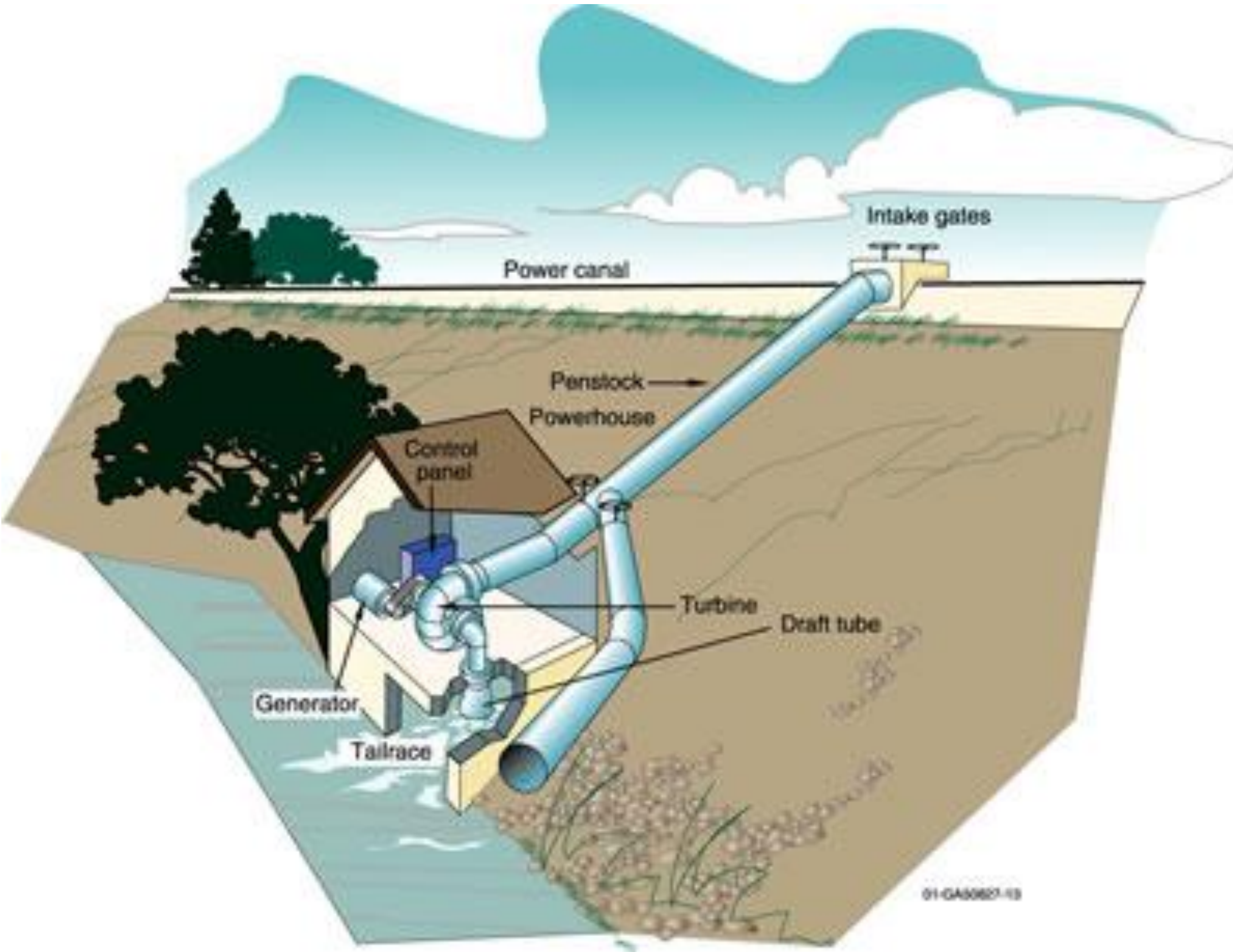


Example

Diversion Hydropower (Tazimina, Alaska)

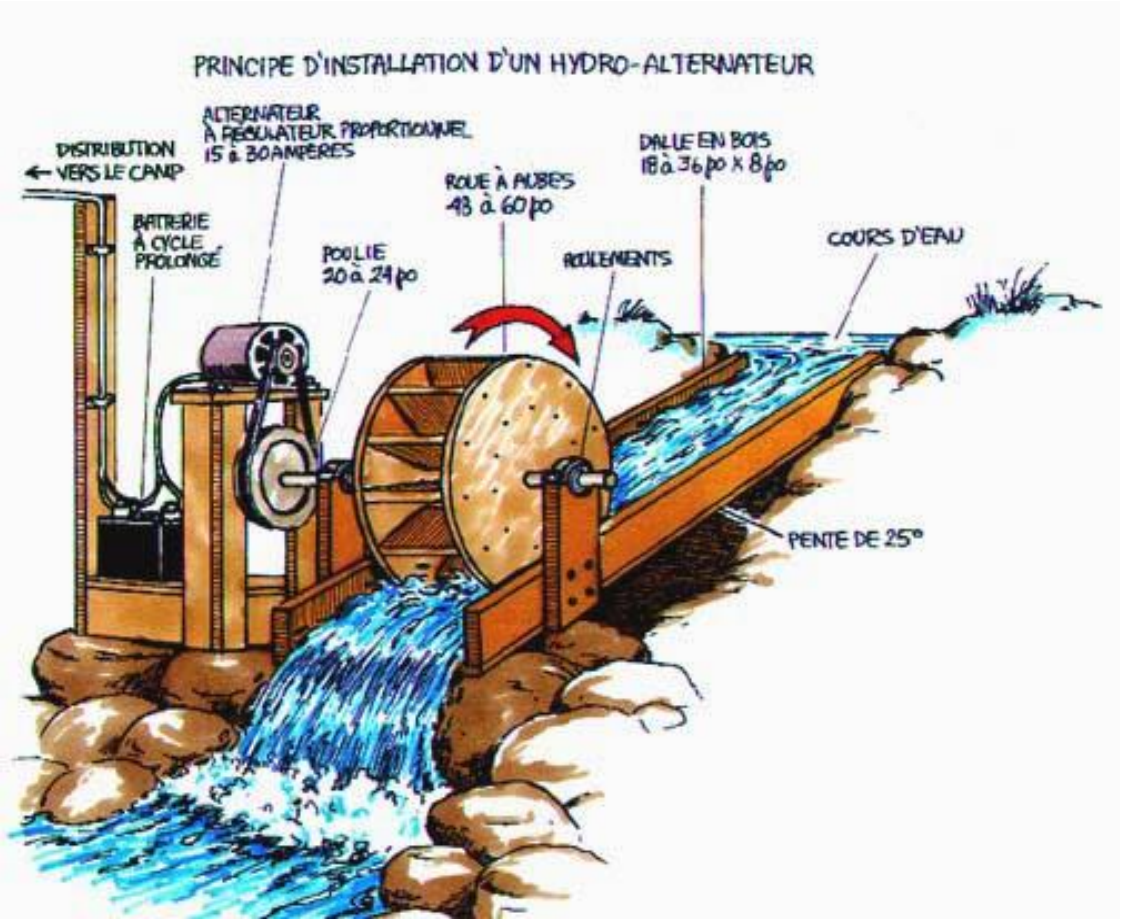
http://www1.eere.energy.gov/windandhydro/hydro_plant_types.html

Micro Run-of-River Hydropower



http://www1.eere.energy.gov/windandhydro/hydro_plant_types.html

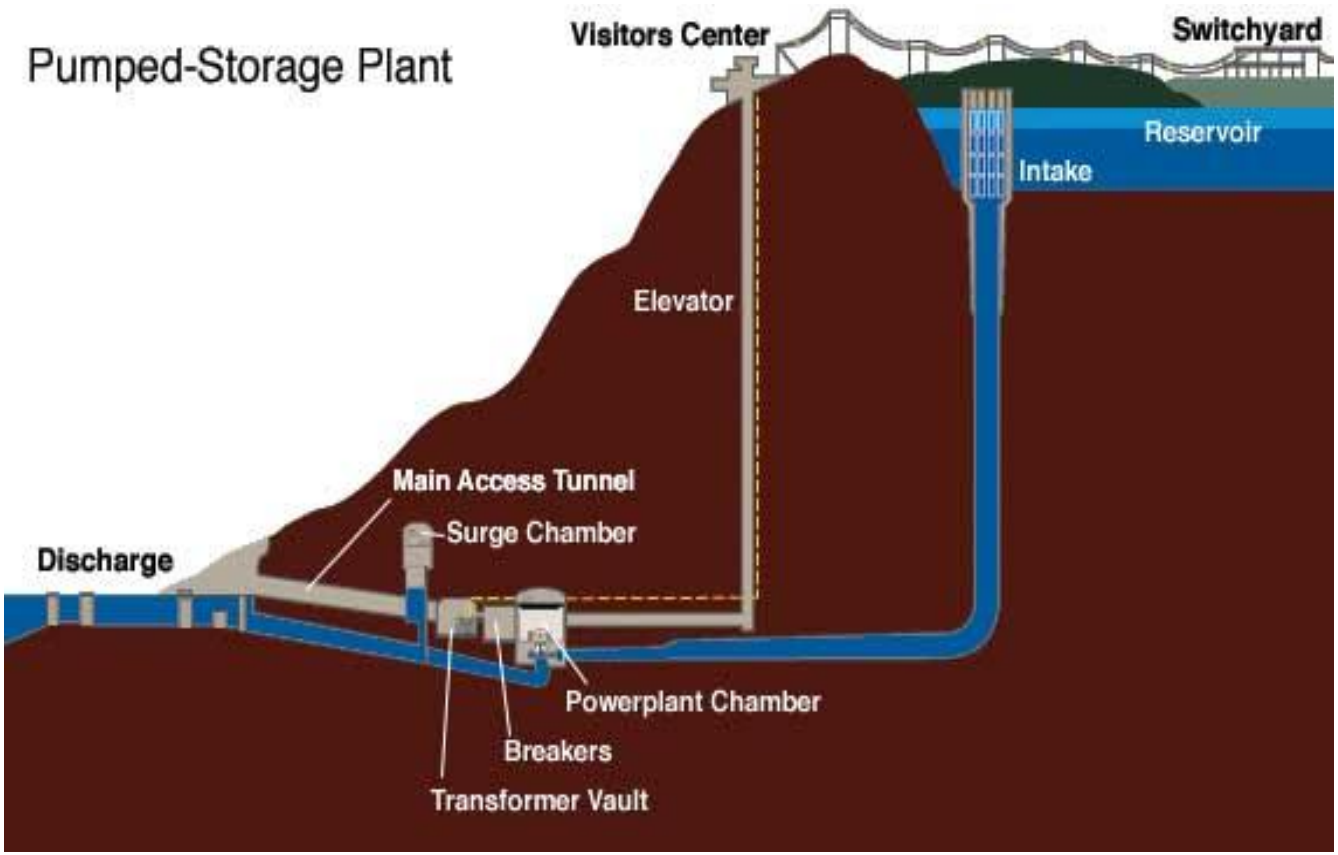
Micro Hydro Example



Used in remote locations in northern Canada

http://www.electrovent.com/#hydrofr

Pumped Storage Schematic



Pumped Storage System

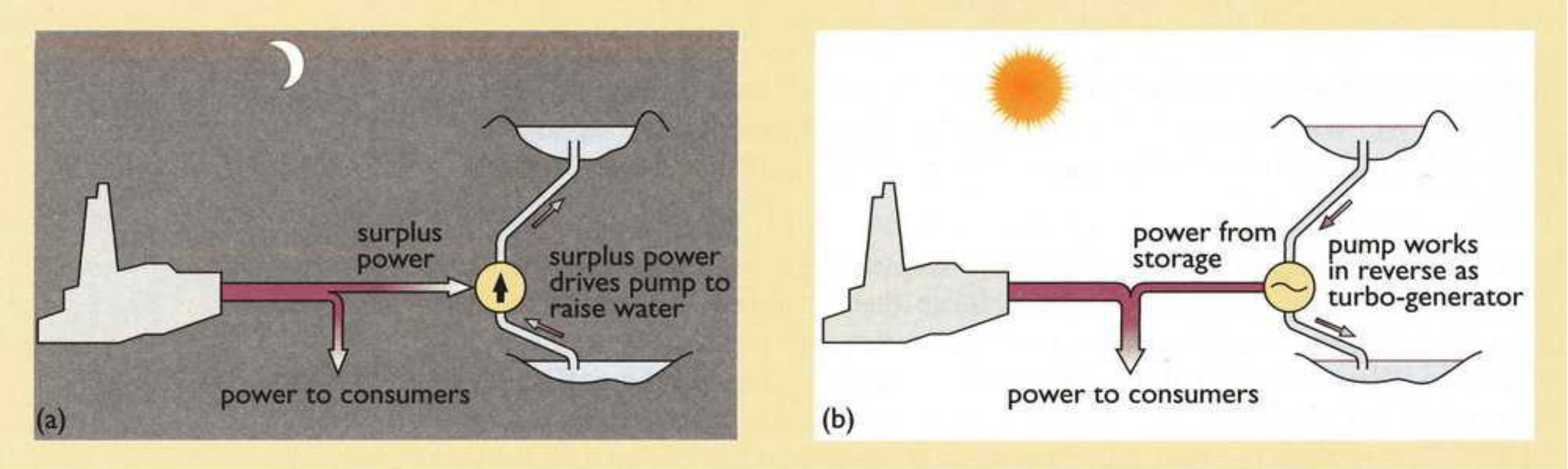


Figure 5.27 Pumped storage system: (a) at time of low demand; (b) at time of high demand

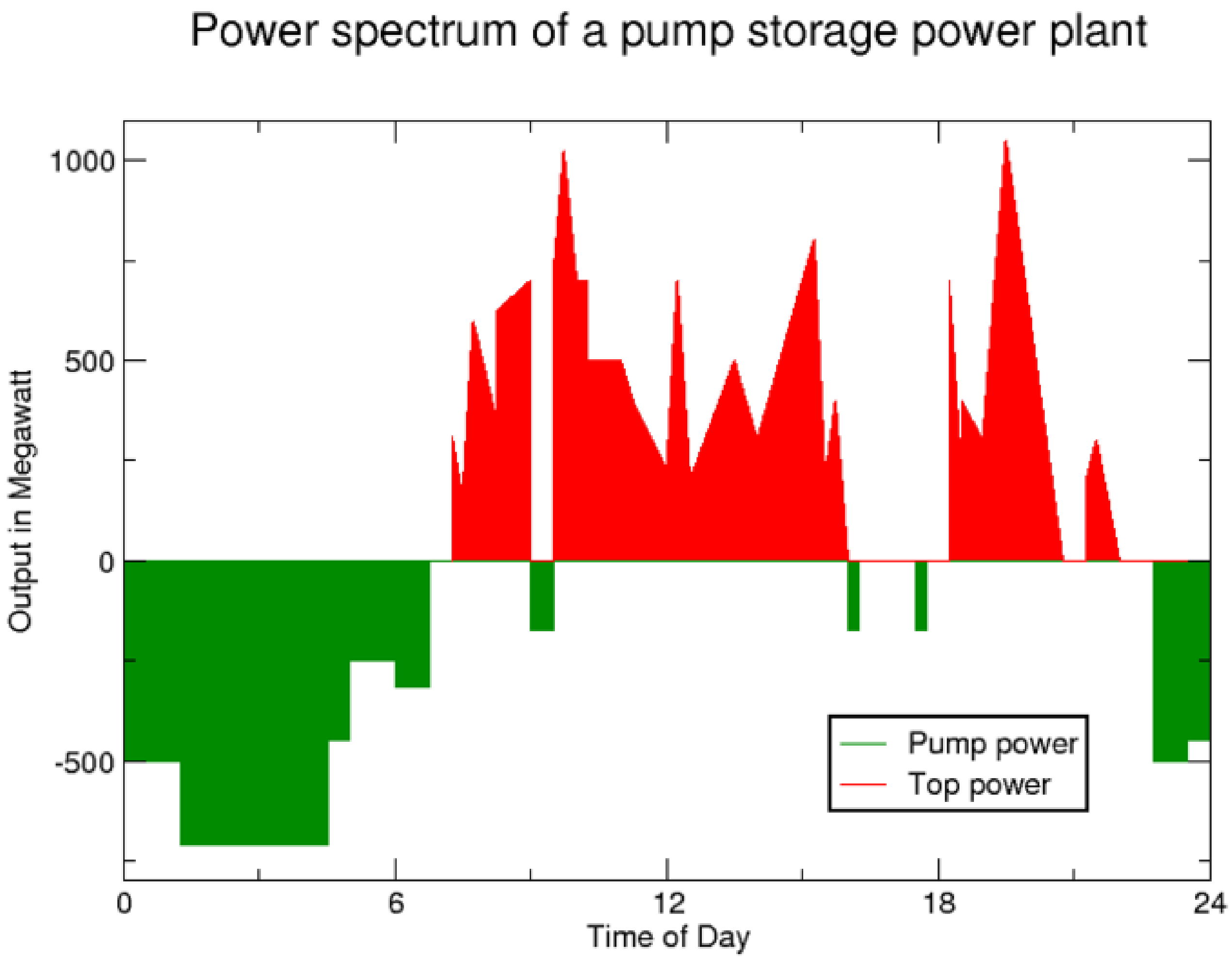
Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Example

Cabin Creek Pumped Hydro (Colorado)

- Completed 1967
- Capacity – 324 MW
  - Two 162 MW units
- Purpose – energy storage
  - Water pumped uphill at night
    - Low usage – excess base load capacity
  - Water flows downhill during day/peak periods
  - Helps Xcel to meet surge demand
    - E.g., air conditioning demand on hot summer days
- Typical efficiency of 70 – 85%

Pumped Storage Power Spectrum



Turbine Design

Francis Turbine
Kaplan Turbine
Pelton Turbine
Turgo Turbine
New Designs

Types of Hydropower Turbines

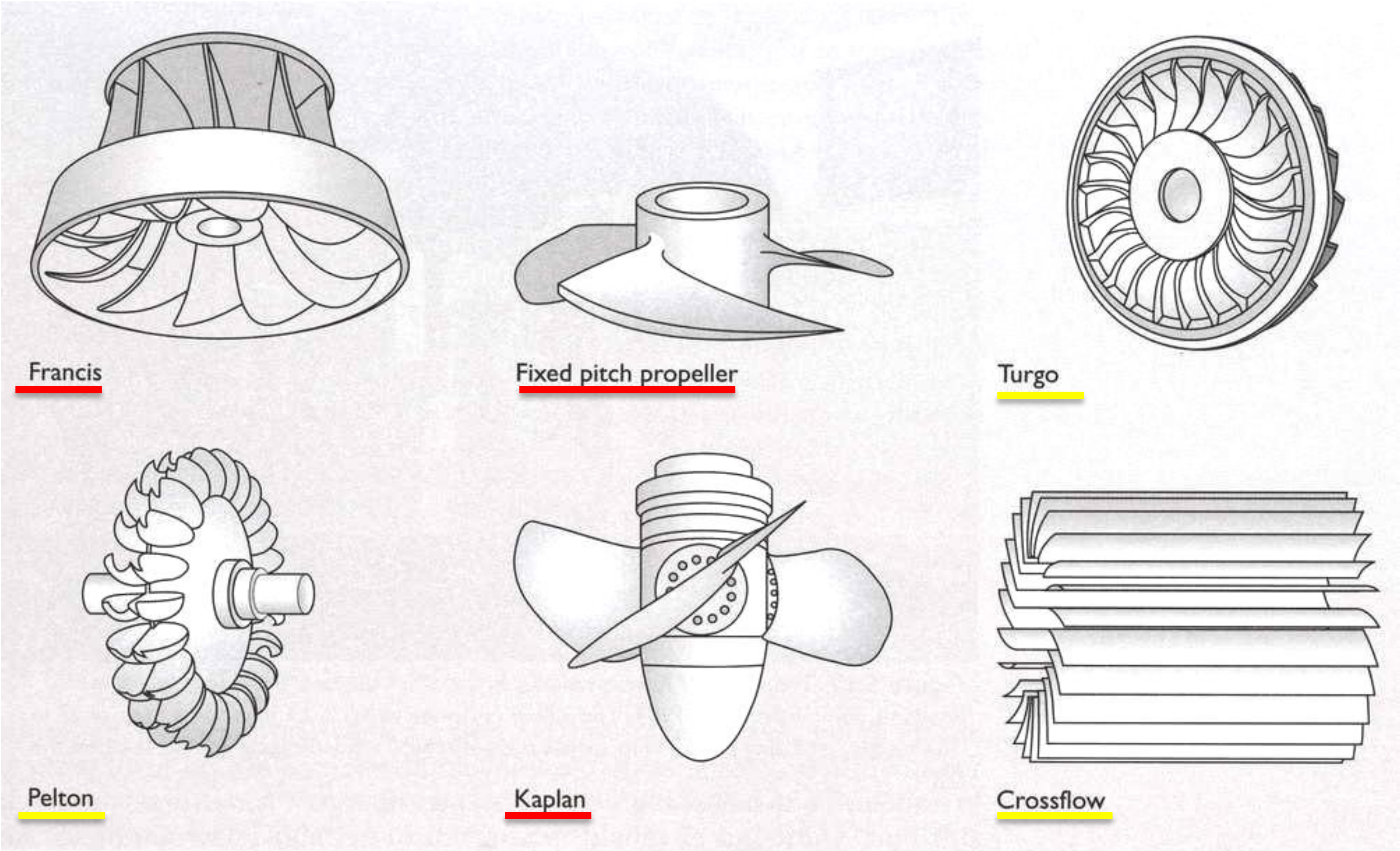


Figure 5.15 Types of turbine runner

Reaction Turbines   Impulse Turbines

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

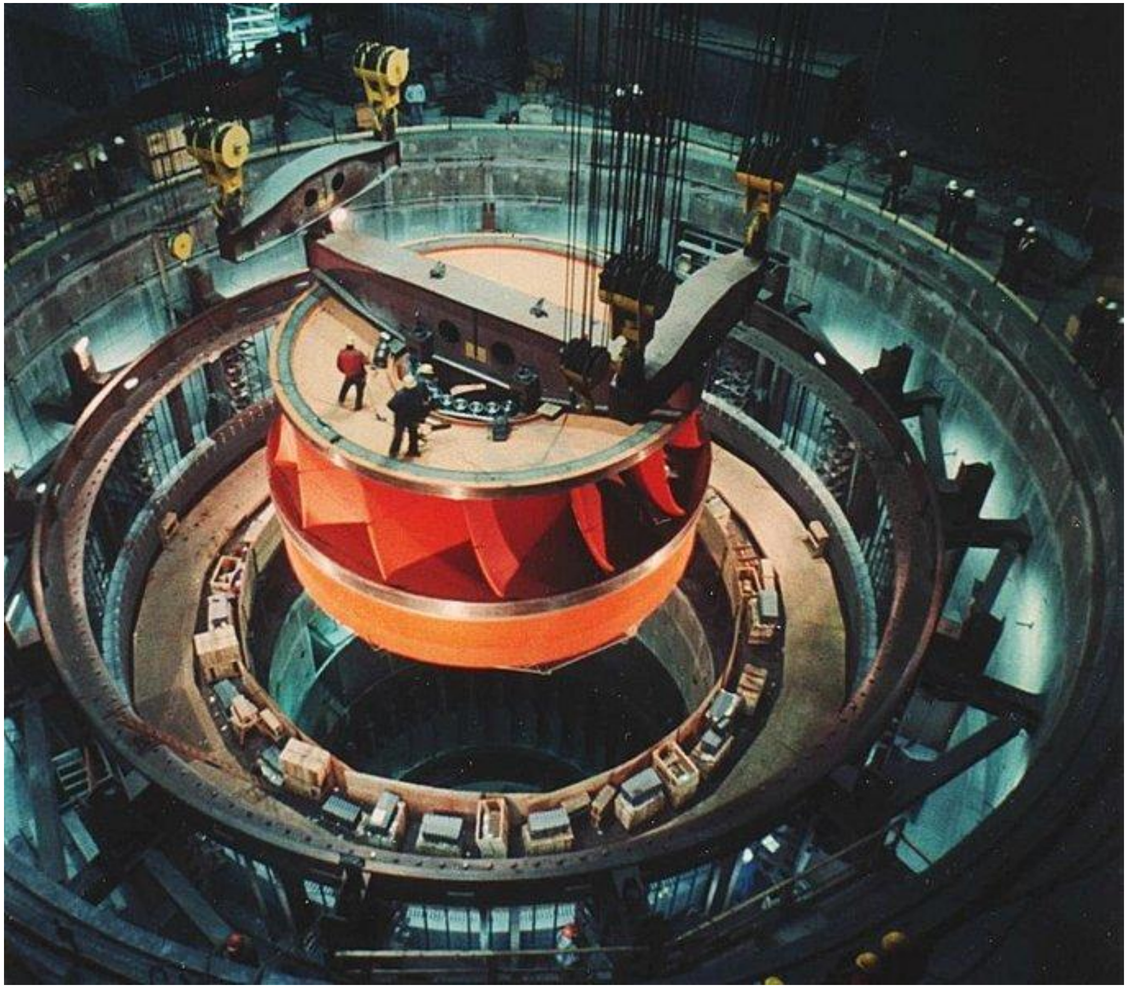
Classification of Hydro Turbines

- Reaction Turbines
  - Derive power from pressure drop across turbine
  - Totally immersed in water
  - Angular & linear motion converted to shaft power
  - Propeller, Francis, and Kaplan turbines
- Impulse Turbines
  - Convert kinetic energy of water jet hitting buckets
  - No pressure drop across turbines
  - Pelton, Turgo, and crossflow turbines

Small Francis Turbine & Generator

"Water Turbine," Wikipedia.com

Francis Turbine – Grand Coulee Dam

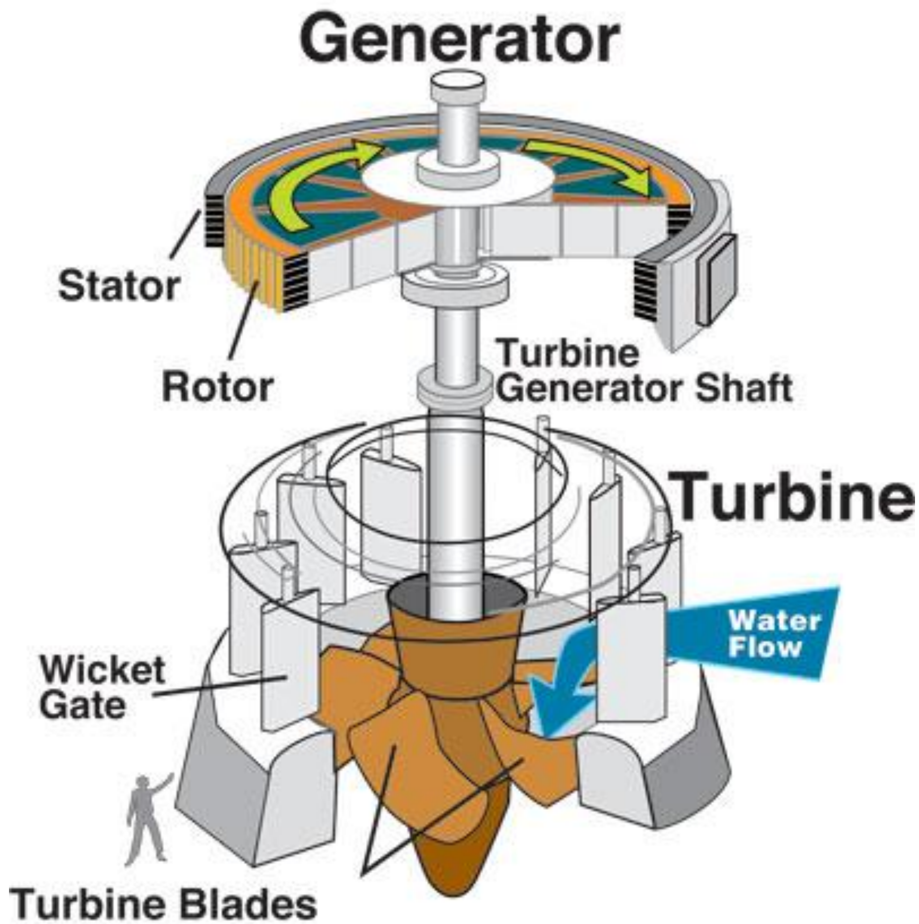


"Water Turbine," Wikipedia.com

Fixed-Pitch Propeller Turbine

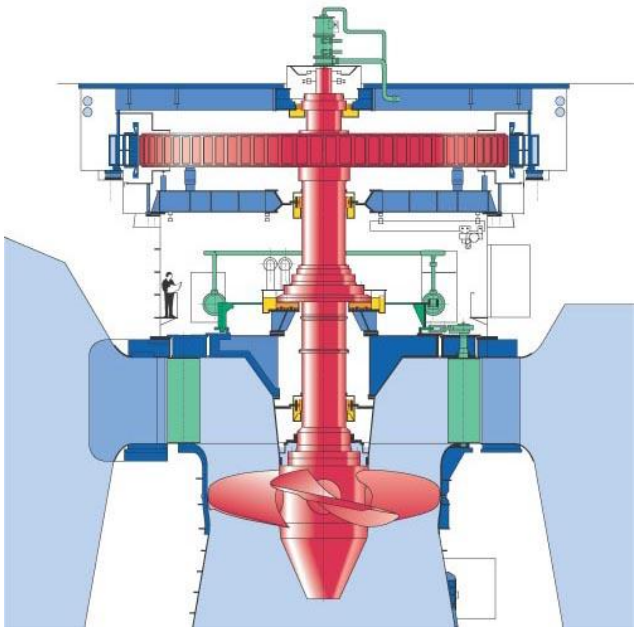
"Water Turbine," Wikipedia.com

Kaplan Turbine Schematic



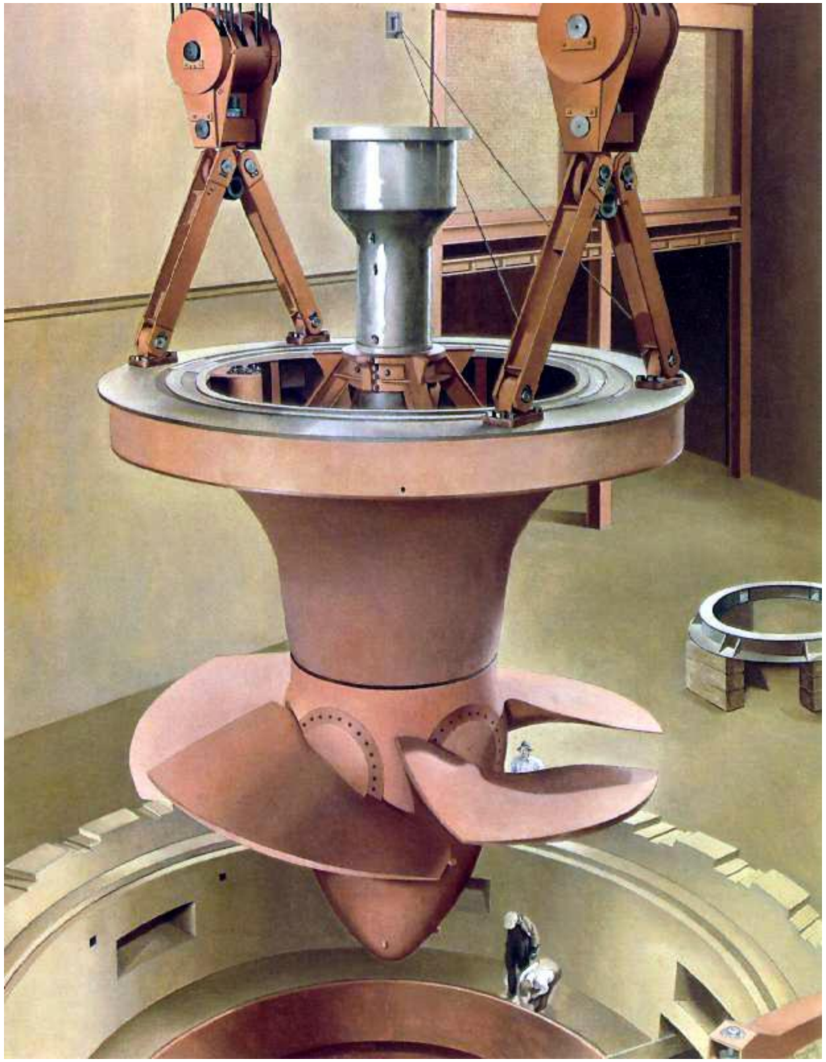
"Water Turbine," Wikipedia.com

Kaplan Turbine Cross Section

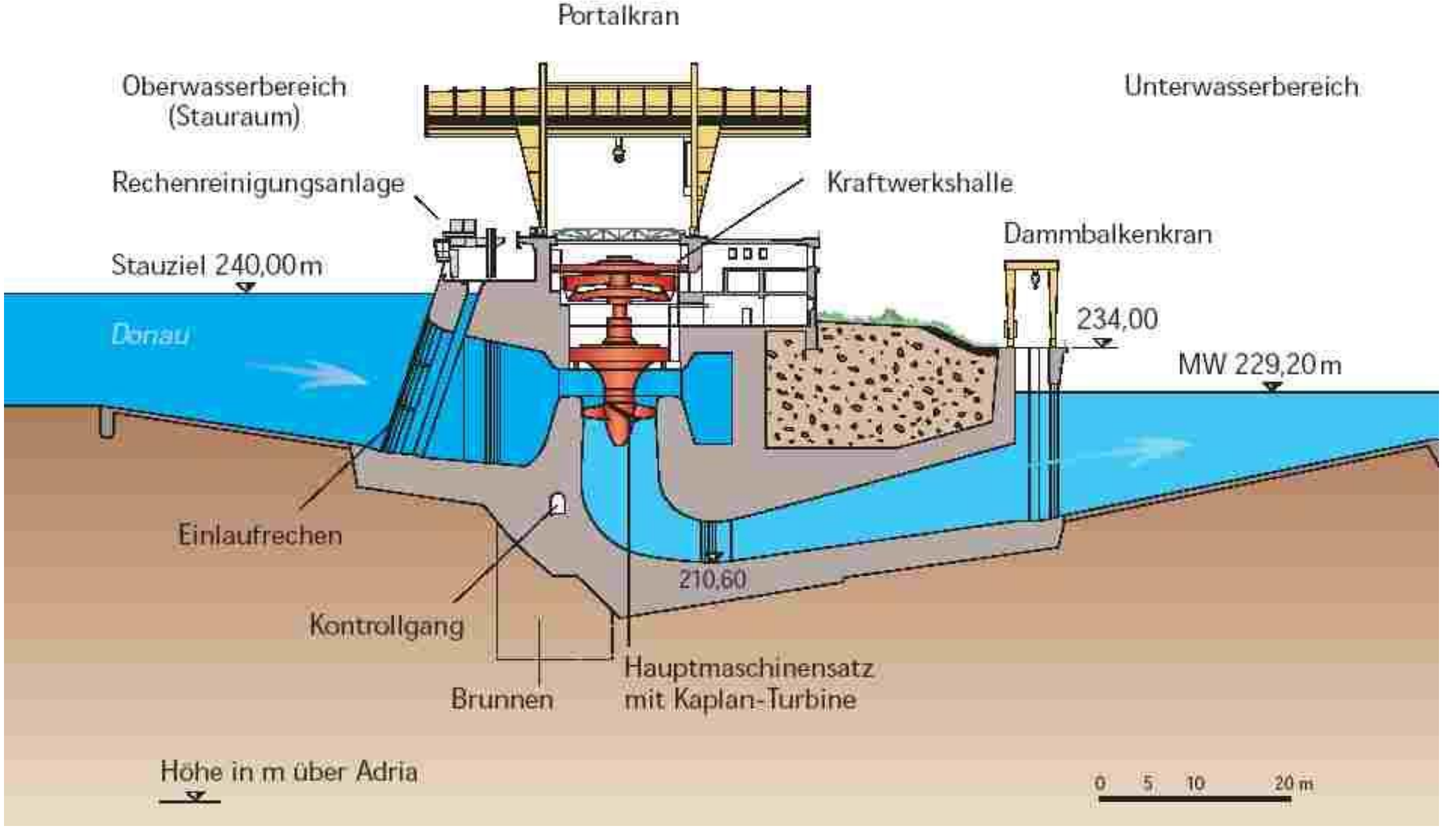


"Water Turbine," Wikipedia.com

Suspended Power, Sheeler, 1939

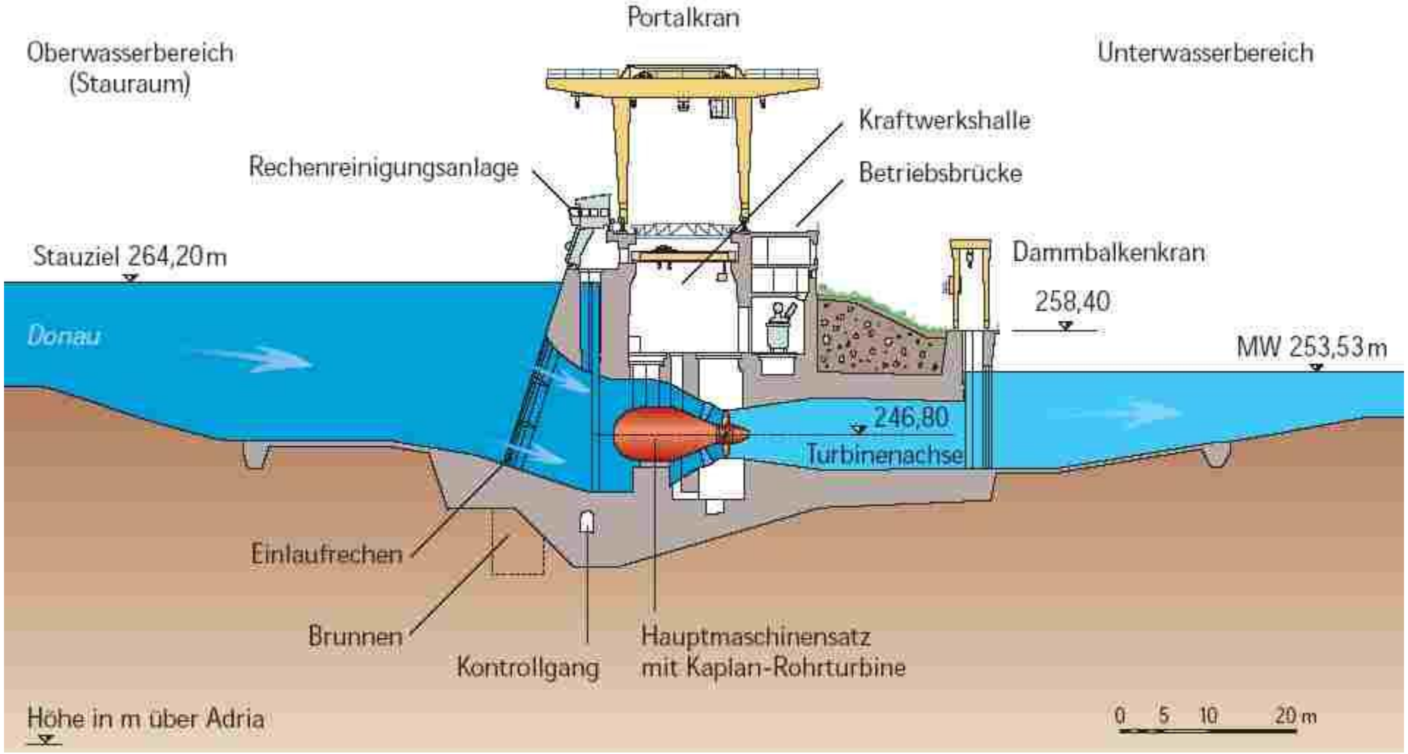


Vertical Kaplan Turbine Setup



Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Horizontal Kaplan Turbine



Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Pelton Wheel Turbine

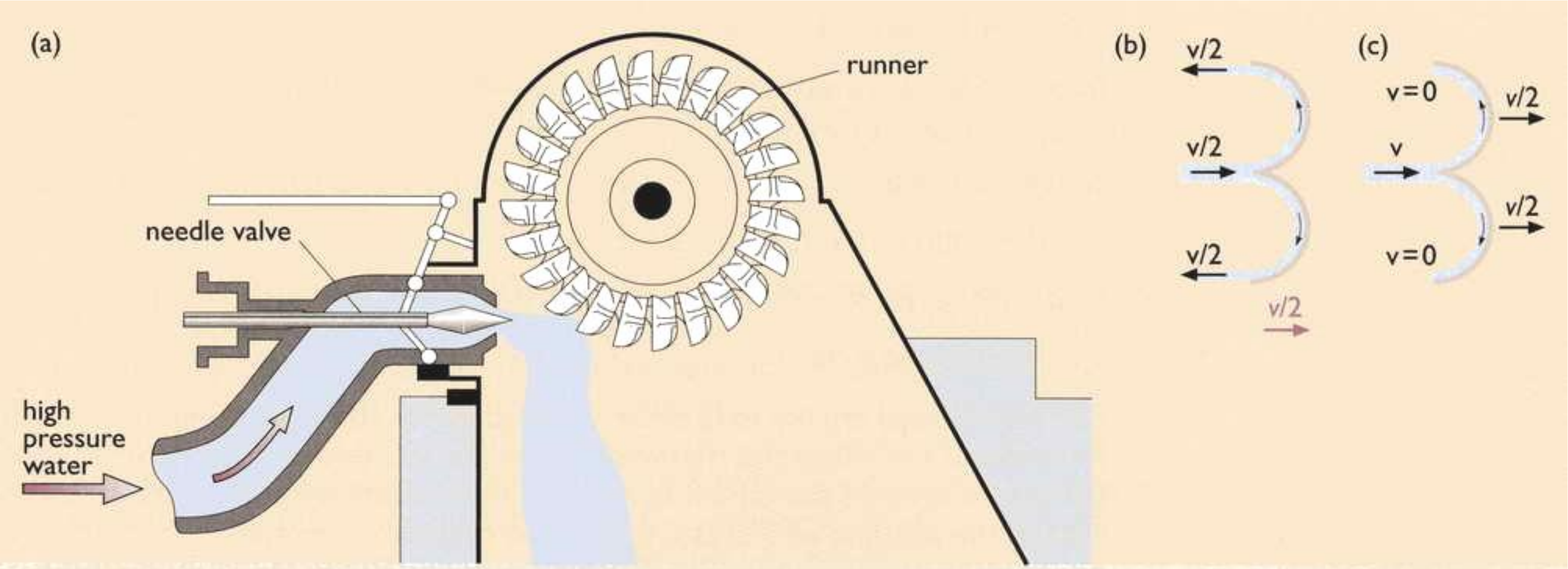


Figure 5.21 Pelton wheel turbine: (a) vertical section; (b) water flow as seen from moving cup; (c) actual motion of water and cup

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Turgo Turbine

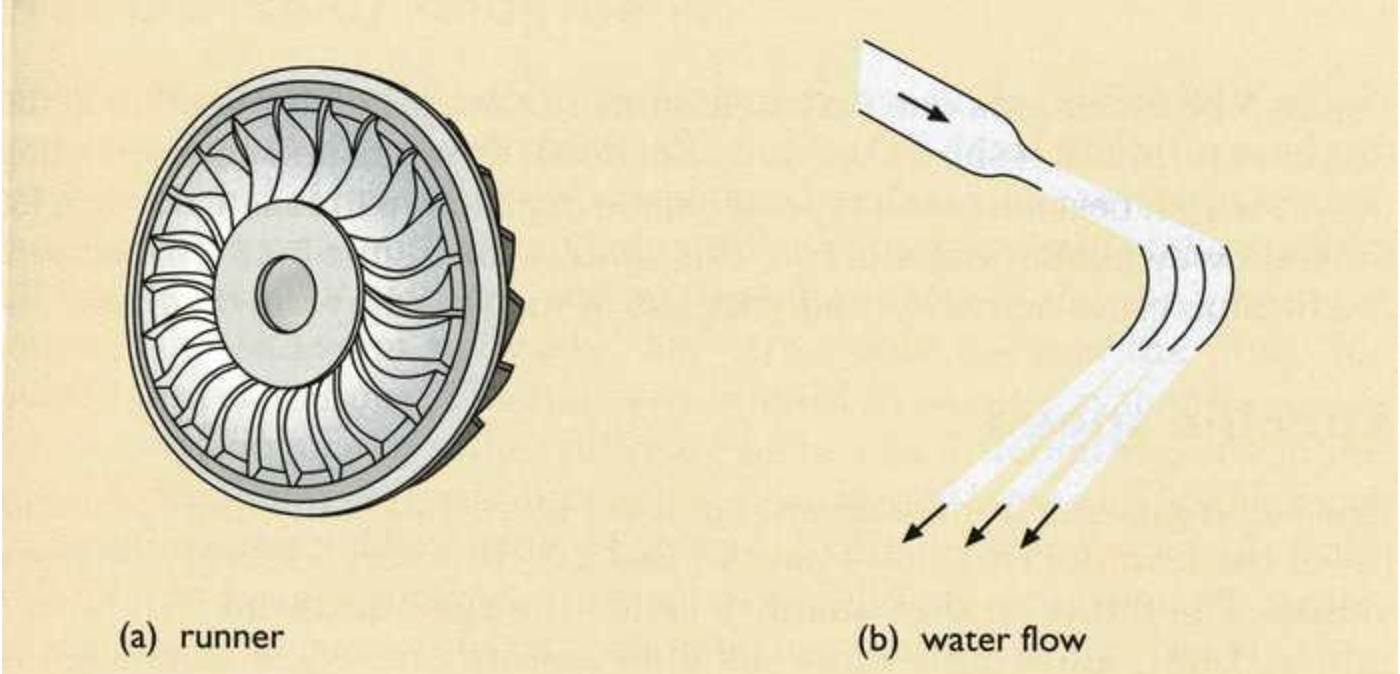


Figure 5.22 Turgo turbine: (a) runner; (b) water flow

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Turbine Design Ranges

Kaplan	$2 < H < 40$
Francis	$10 < H < 350$
Pelton	$50 < H < 1300$
Turgo	$50 < H < 250$

(H = head in meters)

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

Turbine Ranges of Application

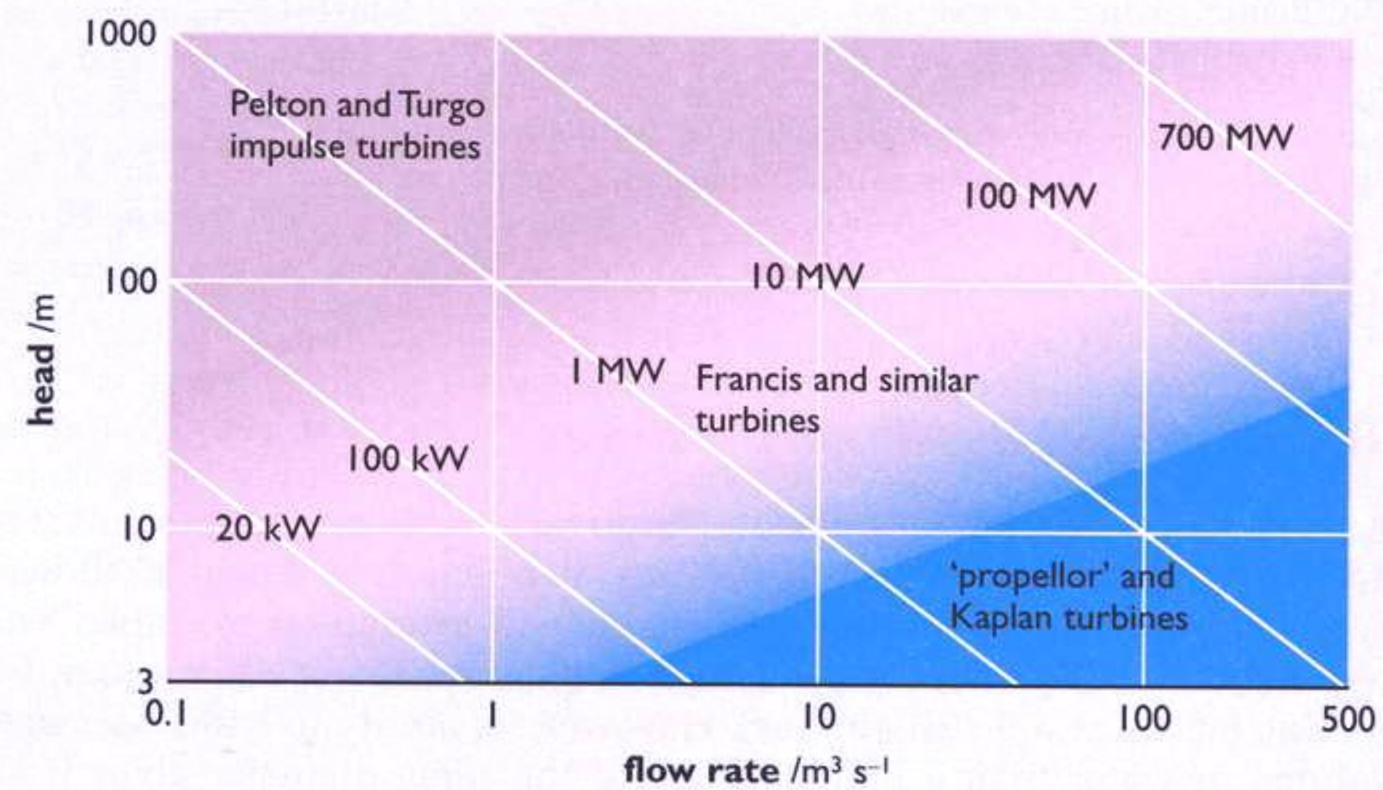


Figure 5.23 Ranges of application of different types of turbine. Note the overlap at the boundaries (see text)

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

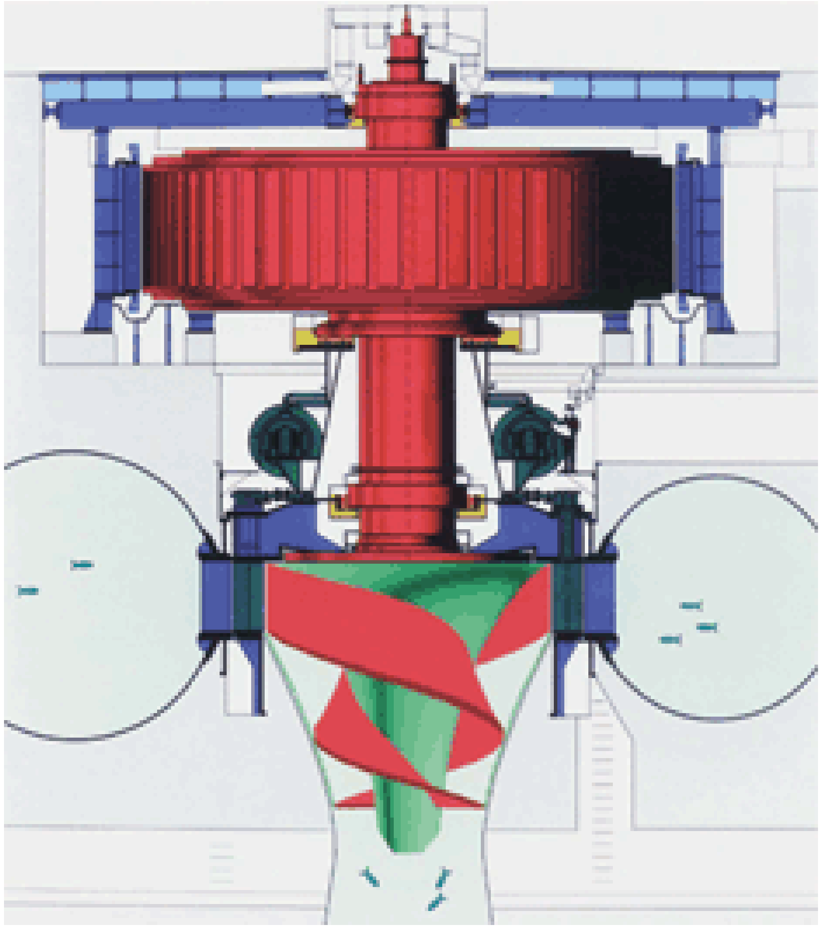
Turbine Design Recommendations

Head Pressure

	High	**Medium**	**Low**
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	Crossflow
Reaction		Francis Pump-as-Turbine	Propeller Kaplan

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Fish Friendly Turbine Design



www.eere.energy.gov/windandhydro/hydro_rd.html

Hydro Power Calculations

Efficiency of Hydropower Plants

- Hydropower is very efficient
  - Efficiency = (electrical power delivered to the "busbar") ÷ (potential energy of head water)
- Typical losses are due to
  - Frictional drag and turbulence of flow
  - Friction and magnetic losses in turbine & generator
- Overall efficiency ranges from 75-95%

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Hydropower Calculations

$$P = g \times \eta \times Q \times H$$

$$P \cong 10 \times \eta \times Q \times H$$

- P = power in kilowatts (kW)
- g = gravitational acceleration (9.81 m/s^2)
- η = turbo-generator efficiency ($0<n<1$)
- Q = quantity of water flowing (m^3/sec)
- H = effective head (m)

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Example 1a

Consider a mountain stream with an effective head of 25 meters (m) *and a flow rate of 600 liters* (ℓ) *per minute. How much power could a hydro plant generate? Assume plant efficiency* (η) *of 83%.*

- H = 25 m
- $Q = 600\ \ell/\text{min} \times 1\ \text{m}^3/1000\ \ell \times 1\ \text{min}/60\text{sec}$
  $= 0.01\ \text{m}^3/\text{sec}$
- $\eta = 0.83$

- $P \cong 10\eta QH = 10(0.83)(0.01)(25) = 2.075$
  $\cong 2.1$ kW

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

Example 1b

How much energy (E) will the hydro plant generate each year?

- $E = P \times t$
  $= 2.1$ kW × 24 hrs/day × 365 days/yr
  $= 18{,}396$ kWh annually

About how many people will this energy support (assume approximately 3,000 kWh / person)?

- People = $E \div 3000$ = 18396/3000 = 6.13
- About 6 people

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

Example 2

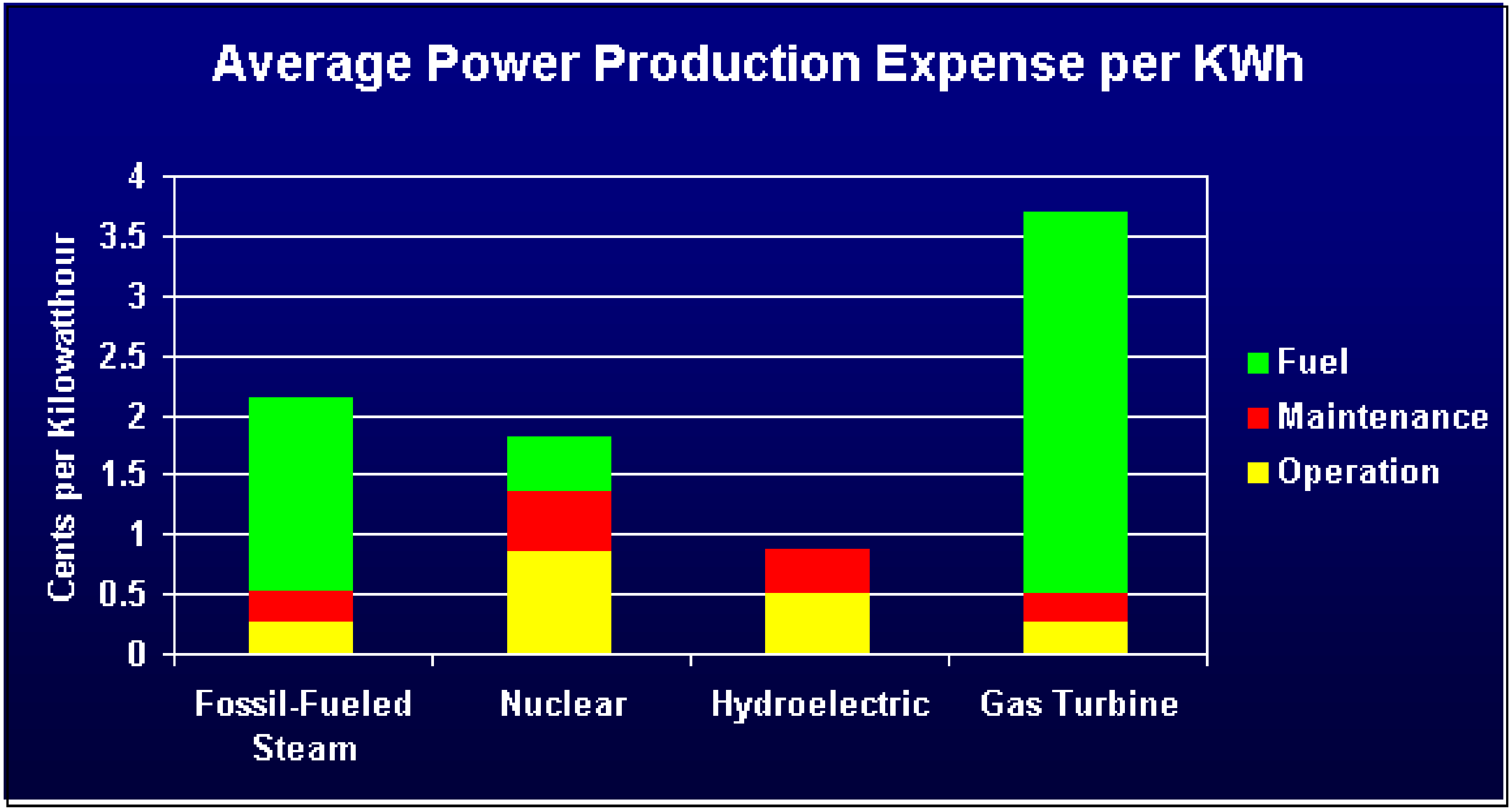
Consider a second site with an effective head of 100 m and a flow rate of 6,000 cubic meters per second (about that of Niagara Falls). Answer the same questions.

- $P \cong 10\eta QH = 10(0.83)(6000)(100)$
  $\cong$ 4.98 million kW = 4.98 GW (gigawatts)
- $E = P \times t = 4.98GW$ × 24 hrs/day × 365 days/yr
  = 43,625 GWh = 43.6 TWh (terrawatt hours)
- People = $E \div 3000$ = 43.6 TWh / 3,000 kWh
  = 1.45 million people
- (This assumes maximum power production 24x7)

Boyle, *Renewable Energy*, 2nd edition, Oxford University Press, 2003

Economics of Hydropower

Production Expense Comparison



Wisconsin Valley Improvement Company, http://www.wvic.com/hydro-facts.htm

Capital Costs of Several Hydro Plants

Table 5.7 Capital costs for three major plants

plant	date	planned capacity	capital cost per kW
Itaipú	1984–91	12.6 GW	$1600
Gabcikovo-Nagymaros[1]	1977–	0.88 GW	$1200
Three Gorges[2]	1993–	18.2 GW	$1200

1 Original data based on the full scheme

2 Expected final cost, stated at completion of the dam in June 2003.

Note that these are for countries where costs are bound to be lower than for fully industrialized countries

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Estimates for US Hydro Construction

- Study of 2000 potential US hydro sites
- Potential capacities from 1-1300 MW
- Estimated development costs
  - $2,000-4,000 per kW
  - Civil engineering 65-75% of total
  - Environmental studies & licensing 15-25%
  - Turbo-generator & control systems ~10%
  - Ongoing costs add ~1-2% to project NPV (!)

Hall *et al.* (2003), *Estimation of Economic Parameters of US Hydropower Resources, Idaho National Laboratory hydropower.id.doe.gov/resourceassessment/ pdfs/project_report-final_with_disclaimer-3jul03.pdf*

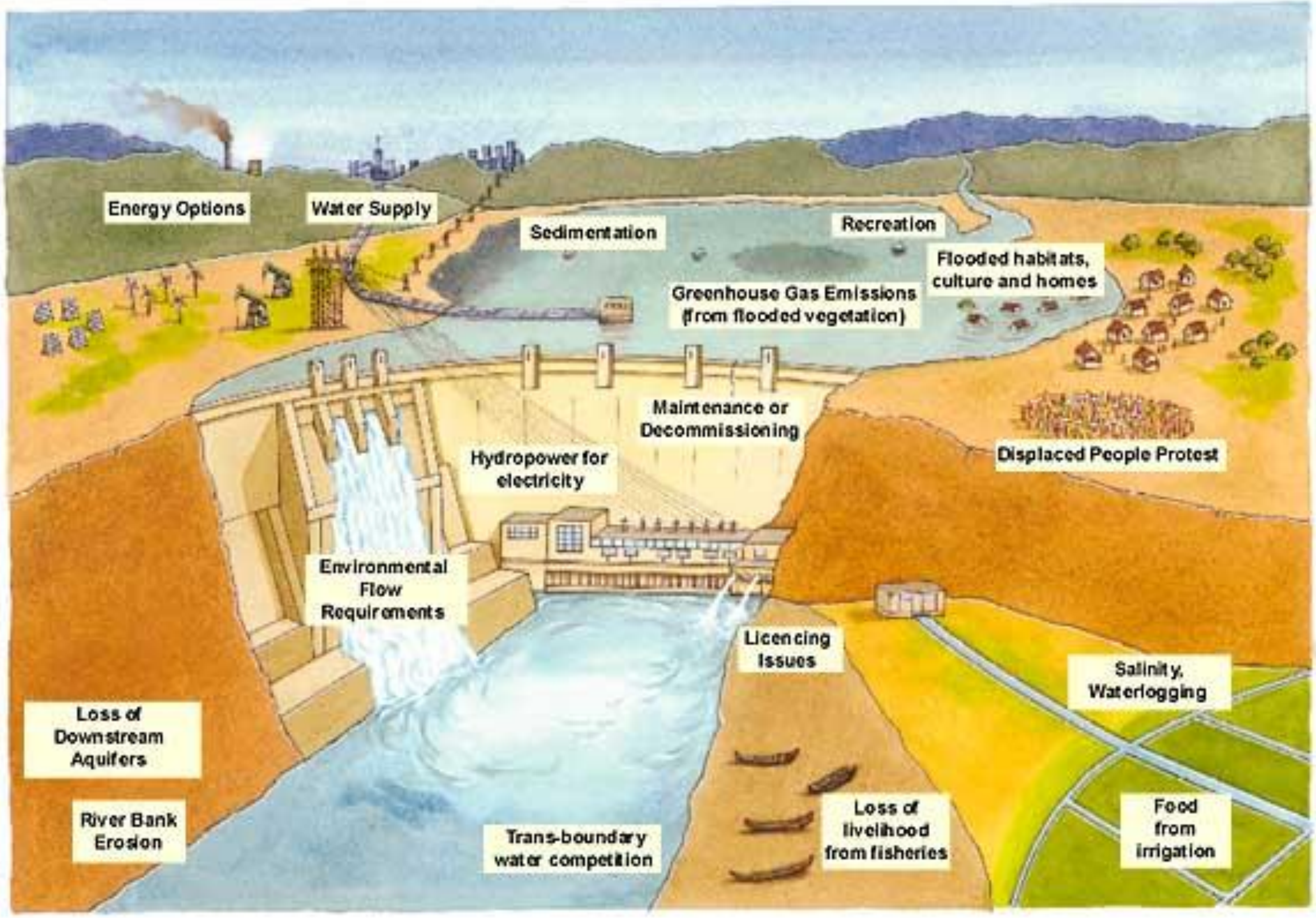
High Upfront Capital Expenses

- 5 MW hydro plant with 25 m low head
  - Construction cost of ~$20 million
  - Negligible ongoing costs
  - Ancillary benefits from dam
    - flood control, recreation, irrigation, etc.
- 50 MW combined-cycle gas turbine
  - ~$20 million purchase cost of equipment
  - Significant ongoing fuel costs
- Short-term pressures may favor fossil fuel energy production

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Environmental Impacts

Impacts of Hydroelectric Dams



Ecological Impacts

- Loss of forests, wildlife habitat, species
- Degradation of upstream catchment areas due to inundation of reservoir area
- Rotting vegetation also emits greenhouse gases
- Loss of aquatic biodiversity, fisheries, other downstream services
- Cumulative impacts on water quality, natural flooding
- Disrupt transfer of energy, sediment, nutrients
- Sedimentation reduces reservoir life, erodes turbines
  - Creation of new wetland habitat
  - Fishing and recreational opportunities provided by new reservoirs

Environmental and Social Issues

- Land use – inundation and displacement of people
- Impacts on natural hydrology
  - Increase evaporative losses
  - Altering river flows and natural flooding cycles
  - Sedimentation/silting
- Impacts on biodiversity
  - Aquatic ecology, fish, plants, mammals
- Water chemistry changes
  - Mercury, nitrates, oxygen
  - Bacterial and viral infections
    - Tropics
- Seismic Risks
- Structural dam failure risks

Hydropower – Pros and Cons

Positive	Negative
Emissions-free, with virtually no CO2, NOX, SOX, 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 capacity	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 KW to 20,000 MW	Health impacts in developing countries
Low operating and maintenance costs	High initial capital costs
Long lifetimes	Long lead time in construction of large projects

Three Gorges – Pros and Cons

Table 5.8 Summary of the arguments in favour of and against the dam

Issue	Criticism	Defense
Cost	The dam will far exceed the official cost estimate, and the investment will be unrecoverable as cheaper power sources become available and lure away ratepayers.	The dam is within budget, and updating the transmission grid will increase demand for its electricity and allow the dam to pay for itself.
Resettlement	Relocated people are worse off than before and their human rights are being violated	15 million people downstream will be better off due to electricity and flood control
Environment	Water pollution and deforestation will increase, the coastline will be eroded and the altered ecosystem will further endanger many species	Hydroelectric power is cleaner than coal burning and safer than nuclear plants and steps will be taken to protect the environment
Local culture and natural beauty	The reservoir will flood many historical sites and ruin the legendary scenery of the gorges and the local tourism industry	Many historical relics are being moved, and the scenery will not change that much.
Navigation	Heavy siltation will clog ports within a few years and negate improvements to navigation	Shipping will become faster, cheaper and safer as the rapid waters are tamed and ship locks are installed.
Power generation	Technological advances have made hydrodams obsolete, and a decentralized energy market will allow ratepayers to switch to cheaper, cleaner power supplies	The alternatives are not viable yet and there is a huge potential demand for the relatively cheap hydroelectricity
Flood control	Siltation will decrease flood storage capacity, the dam will not prevent floods on tributaries, and more effective flood control solutions are available	The huge flood storage capacity will lessen the frequency of major floods. The risk that the dam will increase flooding is remote

Source: ChinaOnLine, 2000

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Environmental Impact, Book page 271

The environmental impact of non-regulated hydro-power is mainly associated with preventing the migration of fish and other biota across the turbine area, but the building of dams in connection with large hydro facilities may have an even more profound influence on the ecology of the region, in addition to introducing accident risks. For large reservoirs, there has been serious destruction of natural landscapes and dislocation of populations living in areas to be flooded. There are ways to avoid some of the problems: Modular construction, where the water is cascaded through several smaller reservoirs has been used, e.g. in Switzerland, with a substantial reduction in the area modified as a result. The reservoirs need not be constructed in direct connection with the generating plants, but can be separate installations placed in optimum locations, with a two-way turbine that uses excess electric production from other regions to pump water up into a high-lying reservoir.

When other generating facilities cannot meet demand, the water is then led back through the turbines. This means that although the water cycle may be unchanged on an annual average basis, considerable seasonal modifications of the hydrological cycle may be involved. The influence of such modifications on the vegetation and climate of the region below the reservoir, which would otherwise receive a water flow at a different time, has to be studied in each individual case. The same may be true for the upper region, for example, owing to increased evaporation in the presence of a full reservoir.

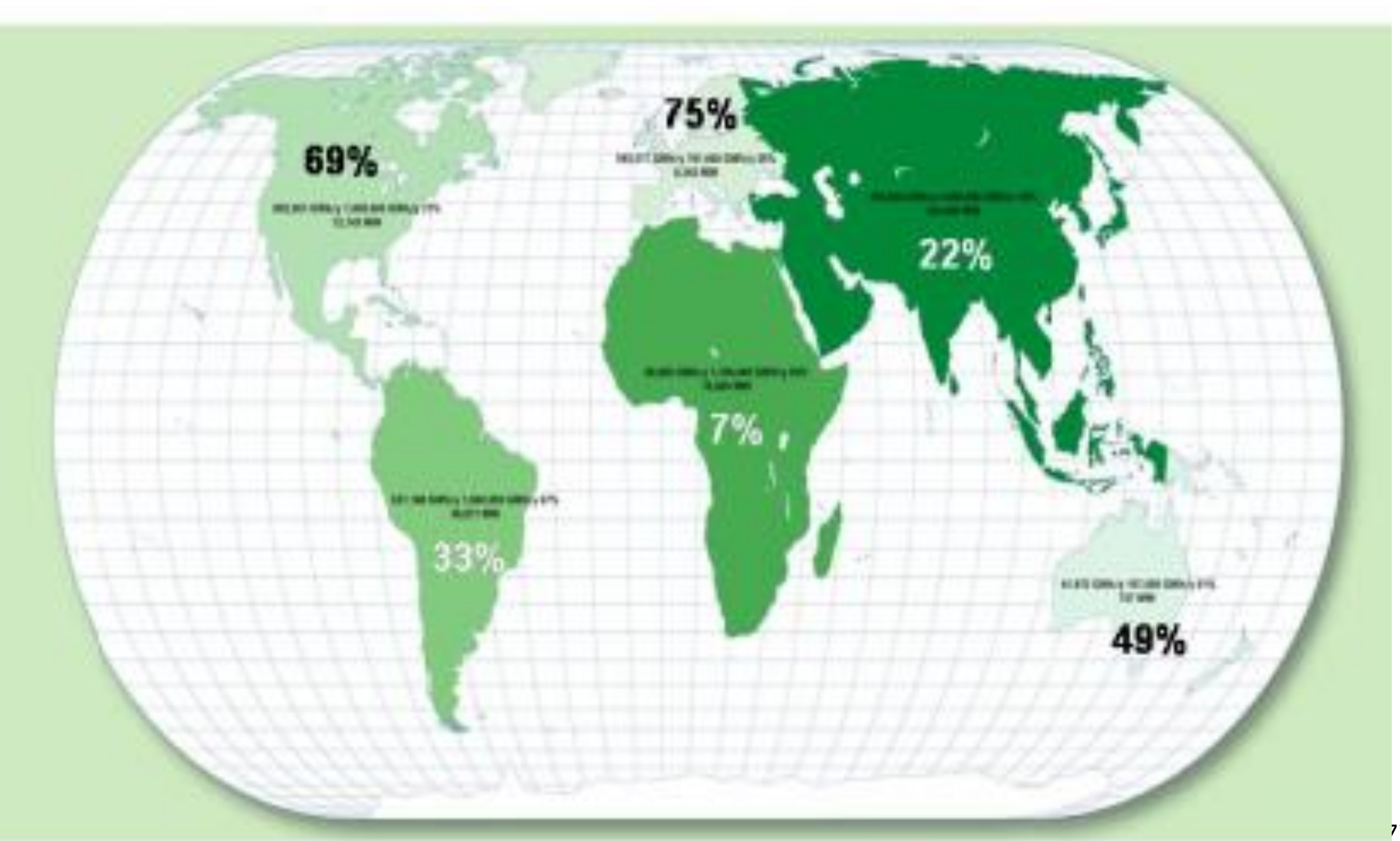
Although these modifications are local, they can influence the ecosystems, with serious consequences for man. An example is provided by the building of the Aswan Dam in Egypt, which has allowed water snails to migrate from the Nile delta to the upstream areas. The water snails may carry parasitic worms causing schistosomiasis, and this disease has actually spread from the delta region to Upper Egypt since the building of the dam (Hayes, 1977).

It is unlikely that hydropower utilization will ever be able to produce changes in the seasonal hydrological cycle which could have global consequences, but no detailed investigation has yet been made.

Future of Hydropower

Hydro Development Capacity

Developed Hydropower Capacity



World Atlas of Hydropower and Dams, 2002

Regional Hydropower Potential

Table 5.3 Regional hydro potential and output

Region	Technical potential /TWh y^{-1}	Annual output* /TWh y^{-1}	Output as percent of technical. potential
Asia	5093	572	11%
S America	2792	507	18%
Europe	2706	729	27%
Africa	1888	80	4.2%
N America	1668	665	40%
Oceania	232	40	17%
World	14379	2593	18%

* Based on average output for the four years 1999–2002

Source: Adapted from WEC, 2003b and BP, 2003

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Opportunities for US Hydropower

Annual Mean Power (MW)	Total	Developed	Excluded	Available[a]
TOTAL POWER	**289,741**	**35,429**	**88,761**	**165,551**
TOTAL HIGH POWER	**229,794**	**34,596**	**76,864**	**118,334**
High Head/High Power	157,772	33,423	55,464	68,885
Low Head/High Power	72,022	1,173	21,400	49,449
TOTAL LOW POWER	**59,947**	**833**	**11,897**	**47,217**
High Head/Low Power	35,403	373	9,163	25,868
Low Head/Low Power	24,544	461	2,734	21,350
Conventional Turbine	8,470	319	899	7,253
Unconventional Systems	3,932	43	527	3,362
Microhydro	12,142	99	1,308	10,735

a. No feasibility or availability assessments have been performed. "Available" only indicates net potential after subtracting developed and excluded potentials from total potential.

Hall, *Hydropower Capacity Increase Opportunities* (presentation), Idaho National Laboratory, 10 May 2005
www.epa.gov/cleanenergy/pdf/hall_may10.pdf

Summary of Future of Hydropower

- *Untapped U.S. water energy resources are immense*
- *Water energy has superior attributes compared to other renewables:*
  - *Nationwide accessibility to resources with significant power potential*
  - *Higher availability = larger capacity factor*
  - *Small footprint and low visual impact for same capacity*
- *Water energy will be more competitive in the future because of:*
  - *More streamlined licensing*
  - *Higher fuel costs*
  - *State tax incentives*
  - *State RPSs, green energy mandates, carbon credits*
  - *New technologies and innovative deployment configurations*
- *Significant added capacity is available at competitive unit costs*
- *Relicensing bubble in 2000-2015 will offer opportunities for capacity increases, but also some decreases*
- *Changing hydropower's image will be a key predictor of future development trends*

Hall, *Hydropower Capacity Increase Opportunities* (presentation), Idaho National Laboratory, 10 May 2005
www.epa.gov/cleanenergy/pdf/hall_may10.pdf

Next Week: **Wind Energy**

Units

Powers of 10

Prefix	*Symbol*	*Value*	*Prefix*	*Symbol*	*Value*
atto	a	10^{-18}	kilo	k	10^{3}
femto	f	10^{-15}	mega	M	10^{6}
pico	p	10^{-12}	giga	G	10^{9}
nano	n	10^{-9}	tera	T	10^{12}
micro	μ	10^{-6}	peta	P	10^{15}
milli	m	10^{-3}	exa	E	10^{18}

G, T, P, E are called milliard, billion, billiard, trillion in Europe, but billion, trillion, quadrillion, quintillion in the USA. M as million is universal.

Extra Hydropower Slides

Included for your viewing pleasure

Major Hydropower Producers

- Canada, 341,312 GWh (66,954 MW installed)
- USA, 319,484 GWh (79,511 MW installed)
- Brazil, 285,603 GWh (57,517 MW installed)
- China, 204,300 GWh (65,000 MW installed)
- Russia, 173,500 GWh (44,700 MW installed)
- Norway, 121,824 GWh (27,528 MW installed)
- Japan, 84,500 GWh (27,229 MW installed)
- India, 82,237 GWh (22,083 MW installed)
- France, 77,500 GWh (25,335 MW installed)

1999 figures, including pumped-storage hydroelectricity

"Hydroelectricity," Wikipedia.org

Types of Water Wheels

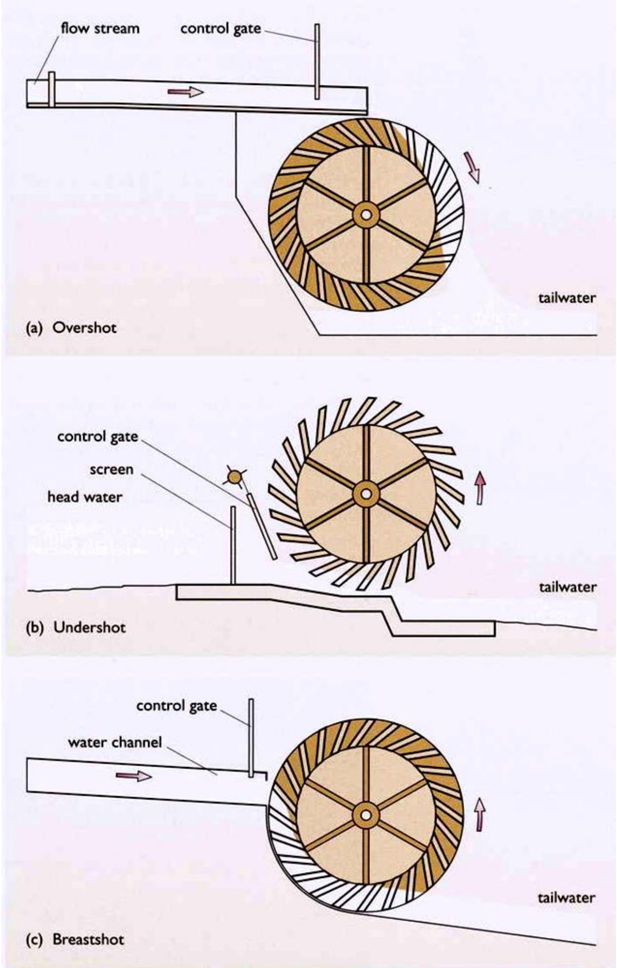
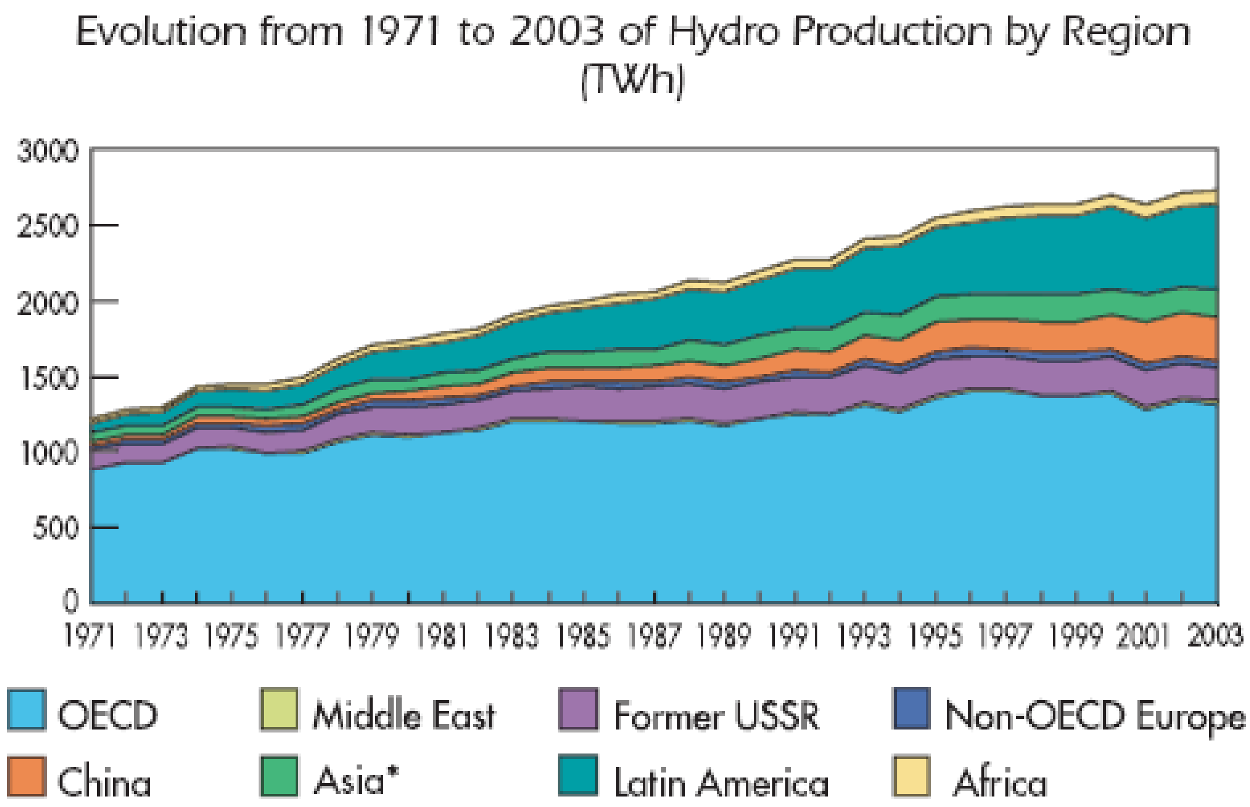


Figure 5.9 Types of traditional water-wheel: (a) overshot; (b) undershot; (c) breastshot

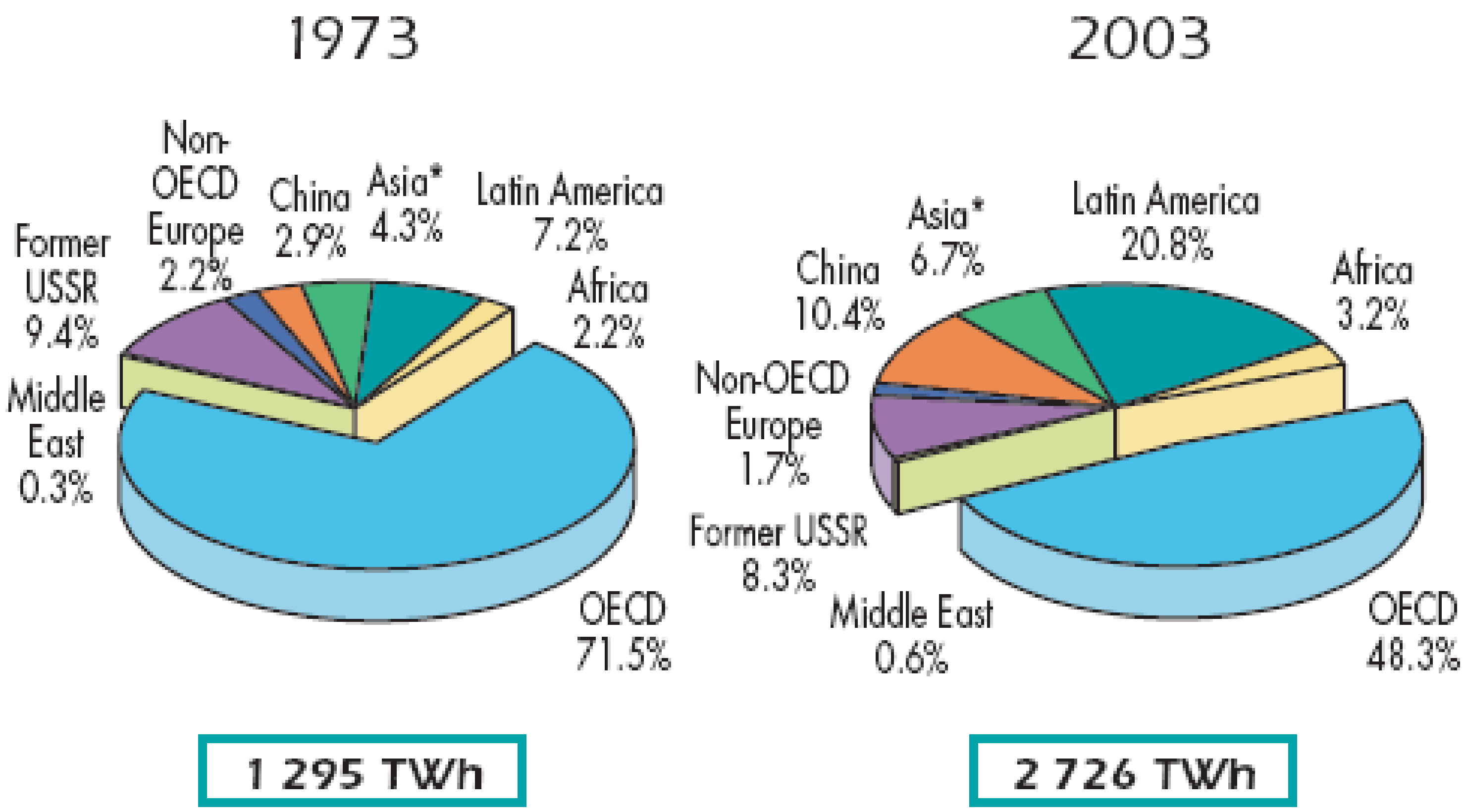
Evolution of Hydro Production



OECD: most of Europe, Mexico, Japan, Korea, Turkey, New Zealand, UK, US

iea.org

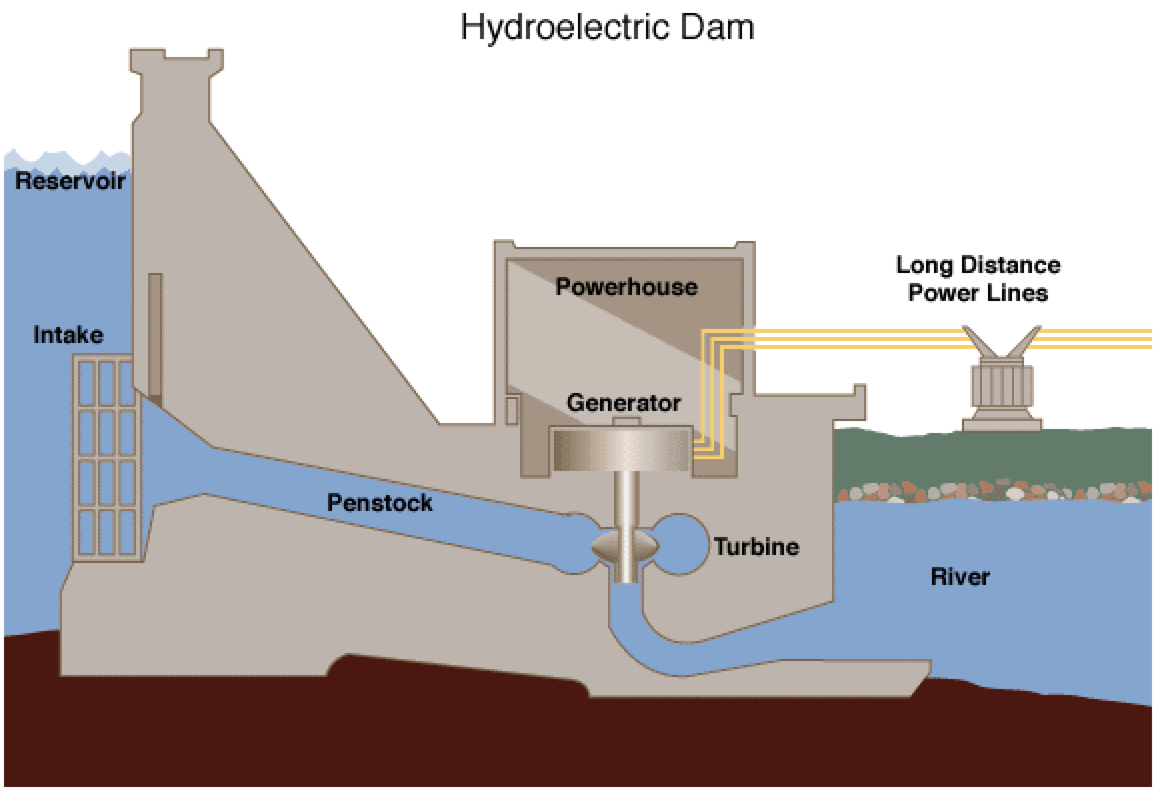
Evolution of Hydro Production



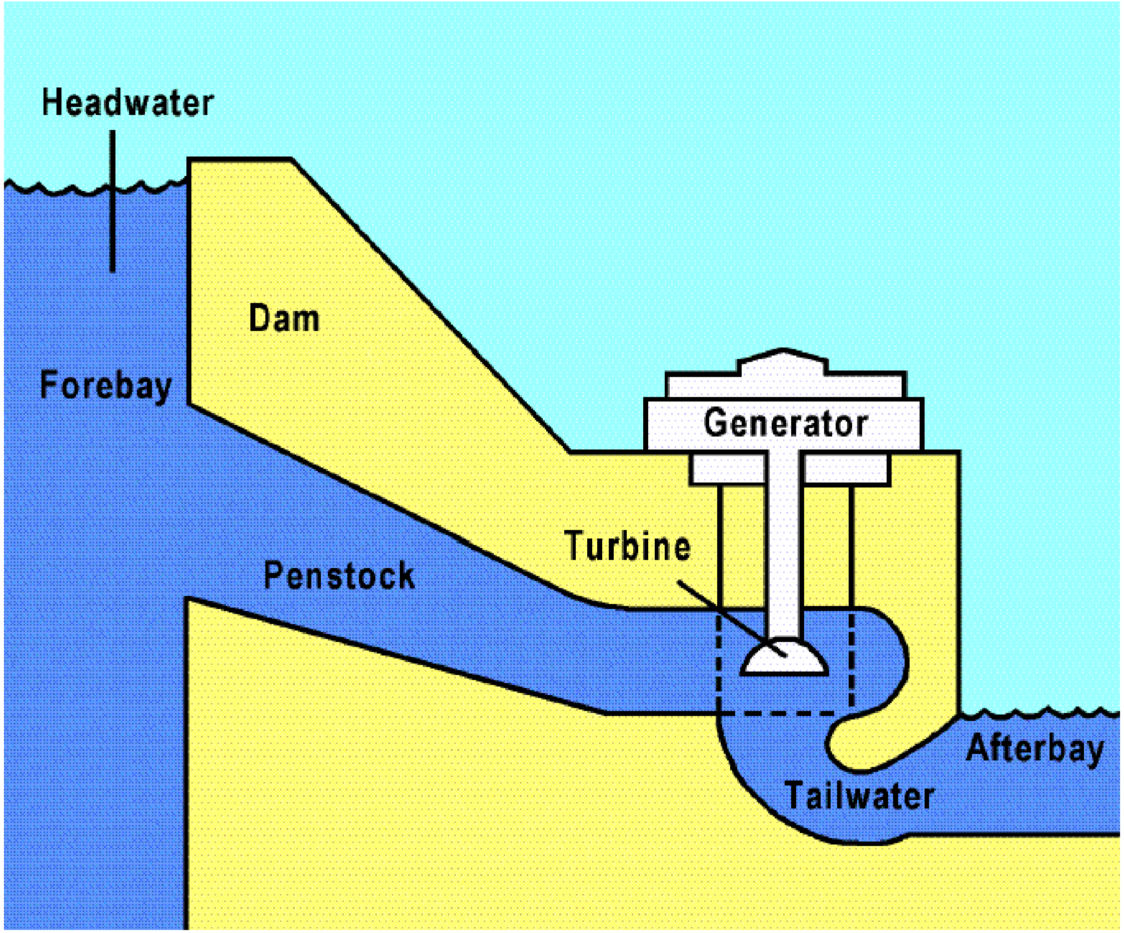
OECD: most of Europe, Mexico, Japan, Korea, Turkey, New Zealand, UK, US

iea.org

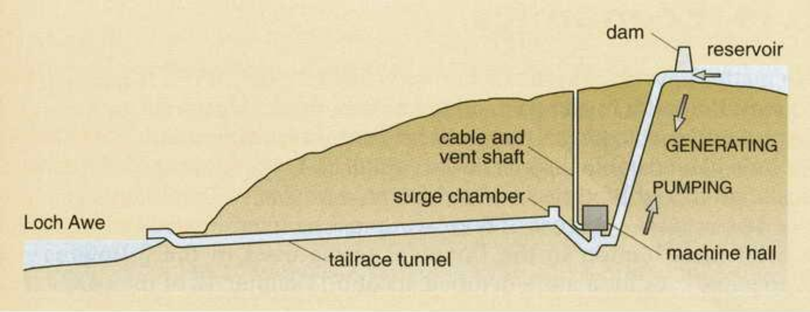
Schematic of Impound Hydropower



Schematic of Impound Hydropower



Cruachan Pumped Storage (Scotland)



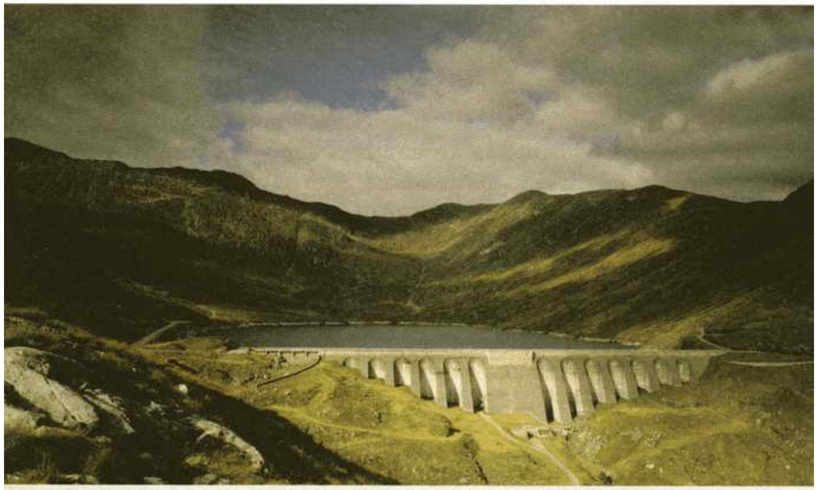


Figure 5.28 Cruachan pumped storage plant. The reservoir of this Scottish plant, commissioned in 1965, can store 10 million cubic metres of water at an operating head of about 370 m. Running the four 100 MW reversible machines for an hour at full capacity, as electric pumps or turbo-generators, raises or lowers reservoir level by about a metre. (top) the installation; (bottom) the dam

Francis Turbine – Grand Coulee

Historically…

- Pumped hydro was first used in Italy and Switzerland in the 1890's.
- By 1933 reversible pump-turbines with motor-generators were available
- Adjustable speed machines now used to improve efficiency
  - Pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days.
  - Efficiency = 70 – 85%

http://www.electricitystorage.org/tech/technologies_technologies_pumpedhydro.htm

Schematic of Francis Turbine

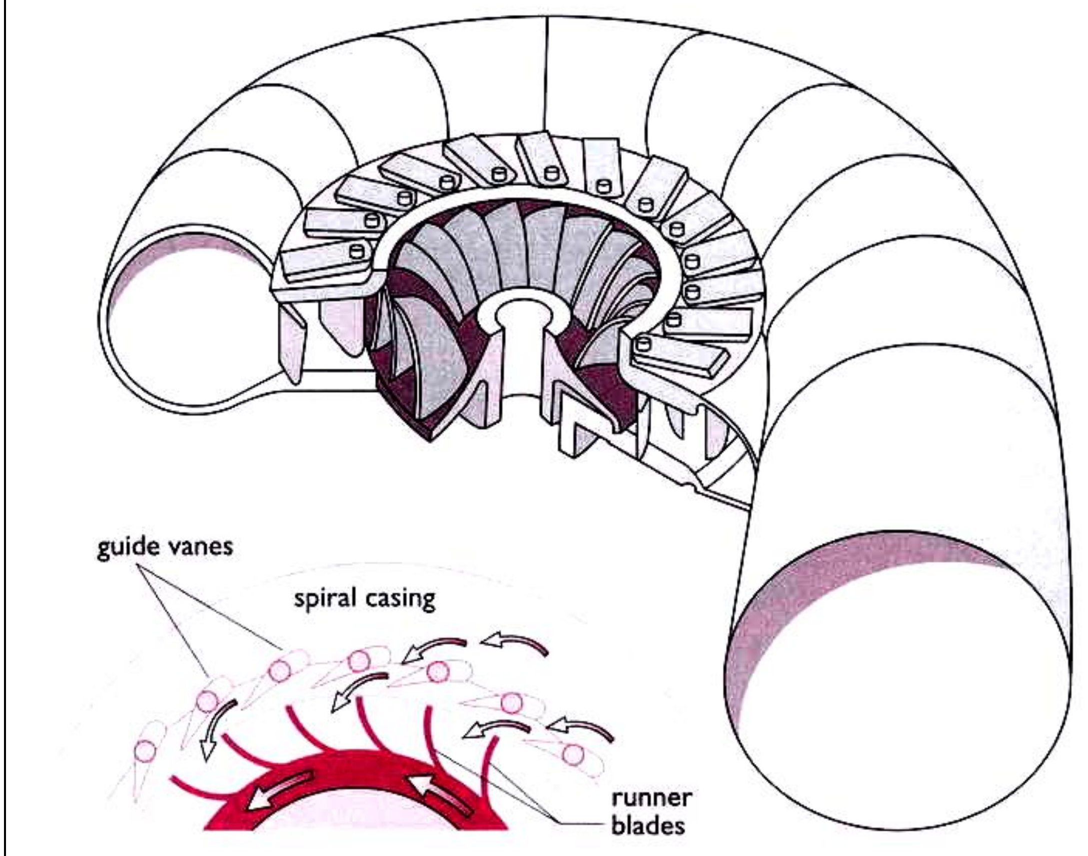
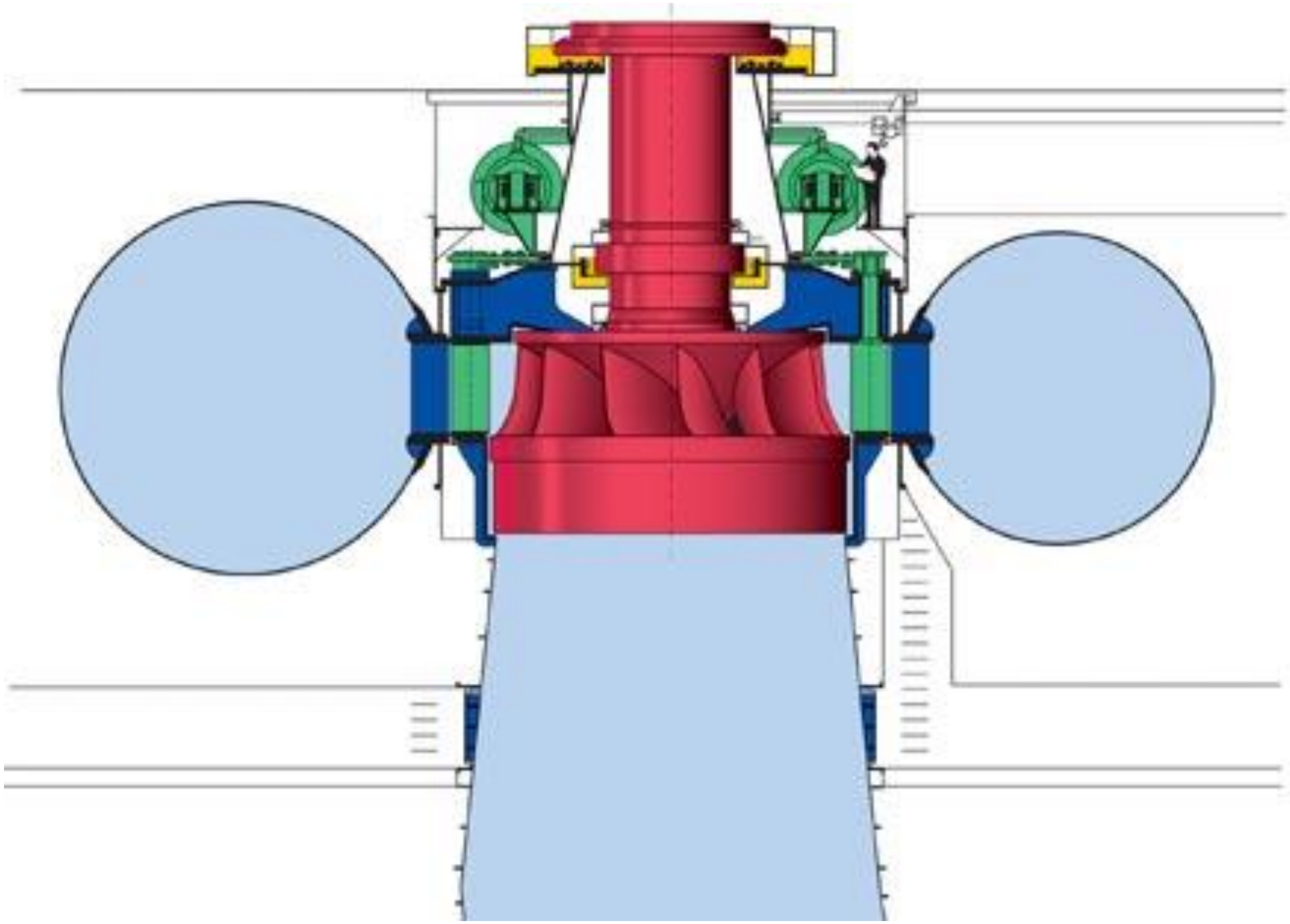


Figure 5.18 Francis turbine: (a) cut-away diagram; (b) flow across guide vanes and runner

Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Francis Turbine Cross-Section



Boyle, *Renewable Energy,* 2nd edition, Oxford University Press, 2003

Small Horizontal Francis Turbine

Figure 5.17 The 450 kW horizontal-axis Francis turbine of a small-scale plant in Scotland, commissioned in 1993. The inflow (at lower right) is 2.1 $m^3 s^{-1}$ at a head of 25 m. The turbine, rotating at 750 rpm, drives the generator whose casing can be seen on the left

Francis and Turgo Turbine Wheels

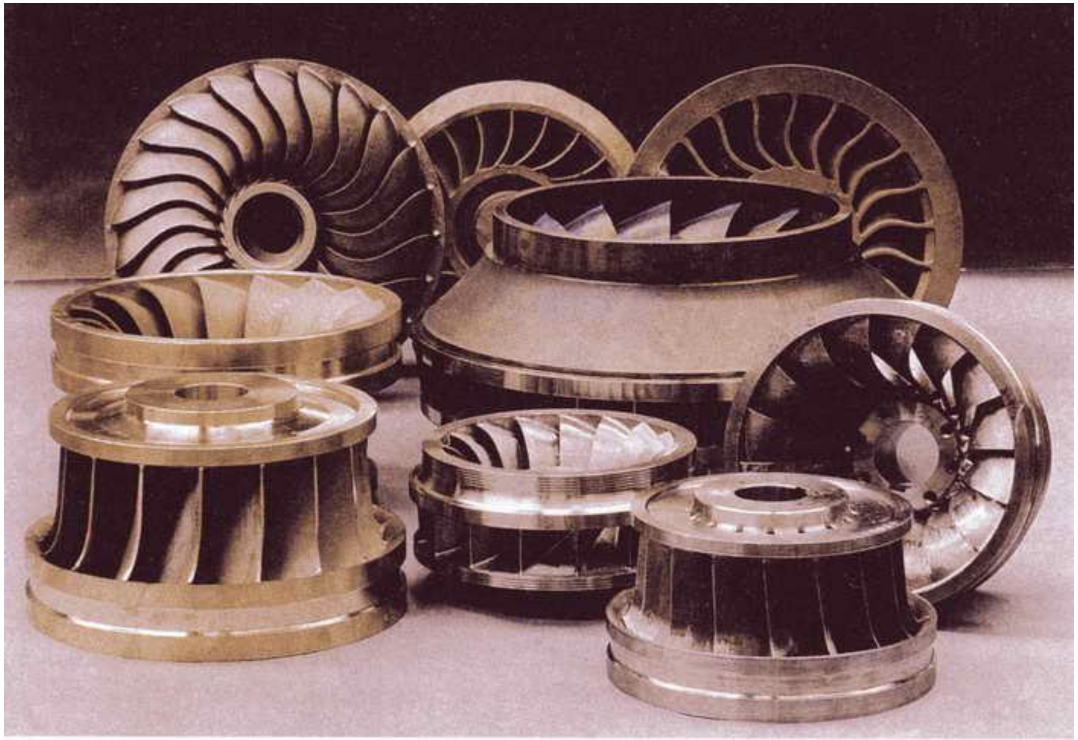


Figure 5.16 Francis and Turgo runners. Front two rows, Francis, from left: pair, 2000 kW output, 80 m head; 600 kW, 80 m; 10.2 MW, 278 m; pair, 412 kW, 29 m. Back row, Turgos: left and right, 1575 kW, 190 m; centre, 428 kW, 175 m

Regulations and Policy

Energy Policy Act of 2005

Hydroelectric Incentives

- Production Tax Credit – 1.8 ¢/KWh
  - For generation capacity added to an existing facility
    - (non-federally owned)
  - Adjusted annually for inflation
  - 10 year payout, $750,000 maximum/year per facility
    - A facility is defined as a single turbine
  - Expires 2016
- Efficiency Incentive
  - 10% of the cost of capital improvement
    - Efficiency hurdle - minimum 3% increase
    - Maximum payout - $750,000
    - One payment per facility
    - Maximum $10M/year
    - Expires 2016
- 5.7 MW proposed through June 2006

World Commission on Dams

- Established in 1998
  - Mandates
    - Review development effectiveness of large dams and assess alternatives for water resources and energy development; and
    - Develop internationally acceptable criteria and guidelines for most aspects of design and operation of dams
- Highly socially aware organization
  - Concern for indigenous and tribal people
  - Seeks to maximize preexisting water and energy systems before making new dams

Other Agencies Involved

- FERC – Federal Energy Regulatory Comm.
  - Ensures compliance with environmental law
- IWRM – Integrated Water & Rsrc Mgmt
  - "Social and economic development is inextricably linked to both water and energy. The key challenge for the 21st century is to expand access to both for a rapidly increasing human population, while simultaneously addressing the negative social and environmental impacts." (IWRM)