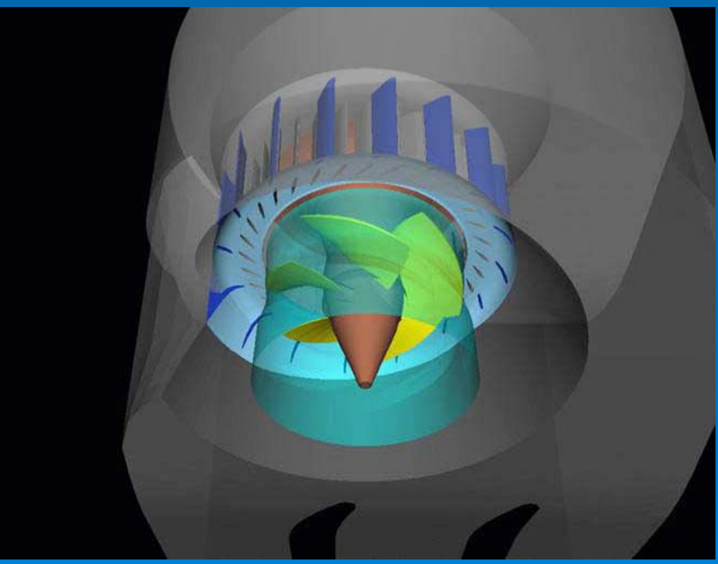
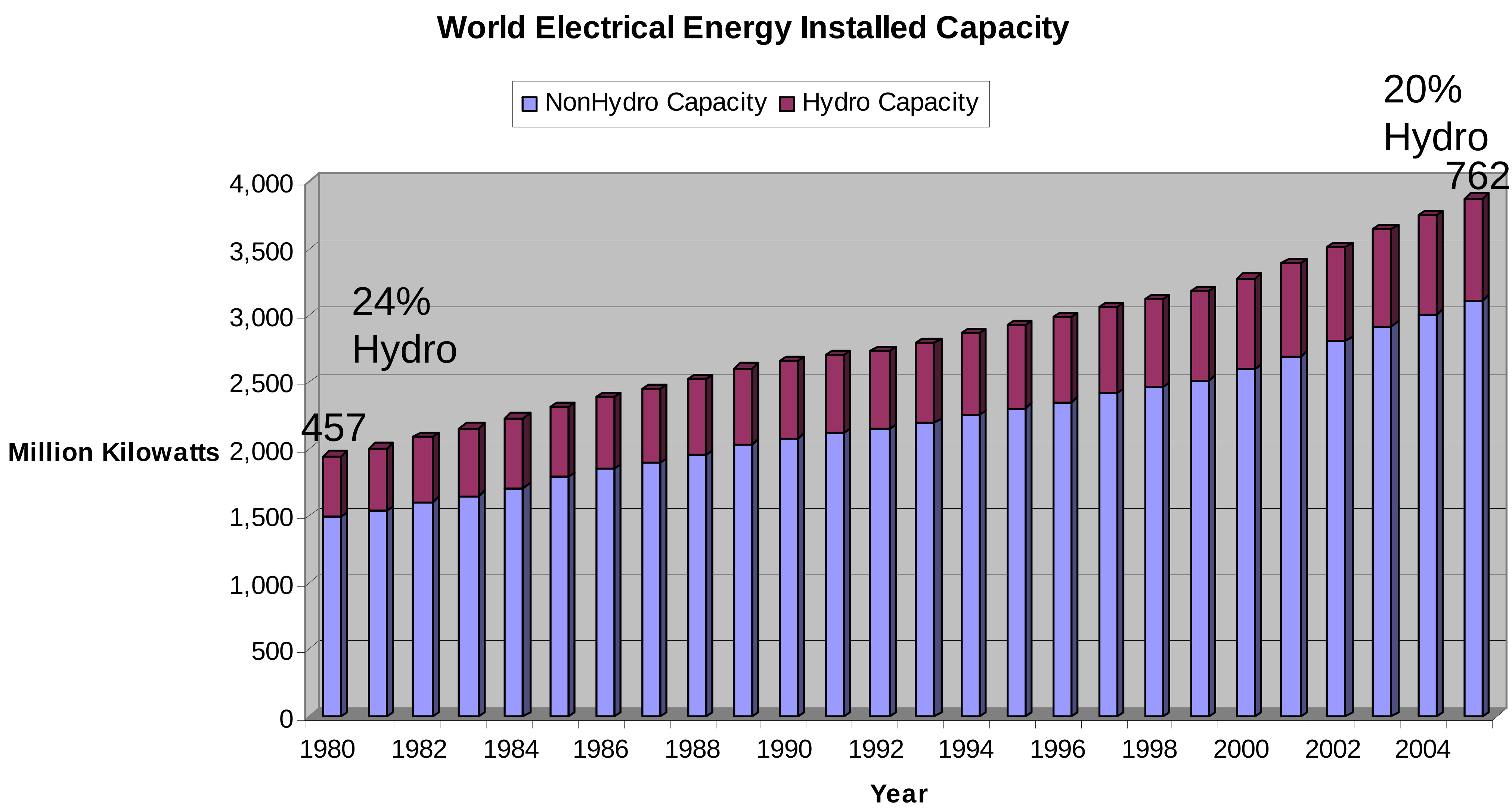
Lecture 5 Hydropower



Hydropower Facts

- Of the ~6.7 B people in the world, at least 2 B people now live without electricity.
- Population is expected to reach 9 billion by 2050.
- By 2020, global electrical energy consumption is projected to grow by 76% (US Energy Info Agency)
- Currently about 20% of the worlds power is produced by hydropower. Currently under development are over 500 projects that will deliver 153 million KW.
- The largest, Three Gorges, will add 18.2 million KW, but hydropower development is occurring in 80 countries.


World Electrical Energy Installed Capacity
NonHydro Capacity
Hydro Capacity
20%
Hydro
762
24%
Hydro
457
Million Kilowatts
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
Year

World's Largest Hydroelectric Plants

(over 4,000 MW capacity)

Name of dam	Location	Rated capacity (MW) Present	Rated capacity (MW) Ultimate	Year of initial operation
Itaipu	Brazil/Paraguay	12,600	14,000	1983
Guri	Venezuela	10,000	10,000	1986
Grand Coulee	Washington	6,494	6,494	1942
Sayano-Shushensk	Russia	6,400	6,400	1989
Krasnoyarsk	Russia	6,000	6,000	1968
Churchill Falls	Canada	5,428	5,428	1971
La Grande 2	Canada	5,328	5,328	1979
Bratsk	Russia	4,500	4,500	1961
Moxoto	Brazil	4,328	4,328	n.a.
Ust-Ilim	Russia	4,320	4,320	1977
Tucurui	Brazil	4,245	8,370	1984

New #1: Three Gorges Dam in China

Beginning in 2009, 26 turbines with a capacity of 18,200 megawatts will produce on average 84.7 terawatt hours a year, which corresponds to the performance of 16 atomic power plants, and will negate the burning of 40-to- 50 million tons of coal annually.

Benefits of Hydropower

- Hydropower is the dominant source of renewable energy and addresses global concerns regarding greenhouse gas emissions and global climate change. In 1997, for example, using hydropower rather than fossil fuels resulted in avoiding emissions that were the equivalent to what all the cars on the planet would have produced for that year.

- Further, many hydropower projects are multipurpose. Flood control, water supply, irrigation, recreation, and navigation are other benefits that may be included in a project. For developing countries, these benefits can be critical to economic development plans and a general desire to raise the population's standard of living.

- And for those responsible for maintaining the electrical grid, hydropower provides an important means of regulating the flow of electricity. Unlike plants that use fossil fuels, hydropower facilities can quickly increase and decrease the amount of electricity being generated. As electric systems must always maintain an exact balance with demand, this "peaking" ability is very important. The operating costs of these plants are also lower than those using fossil fuels.

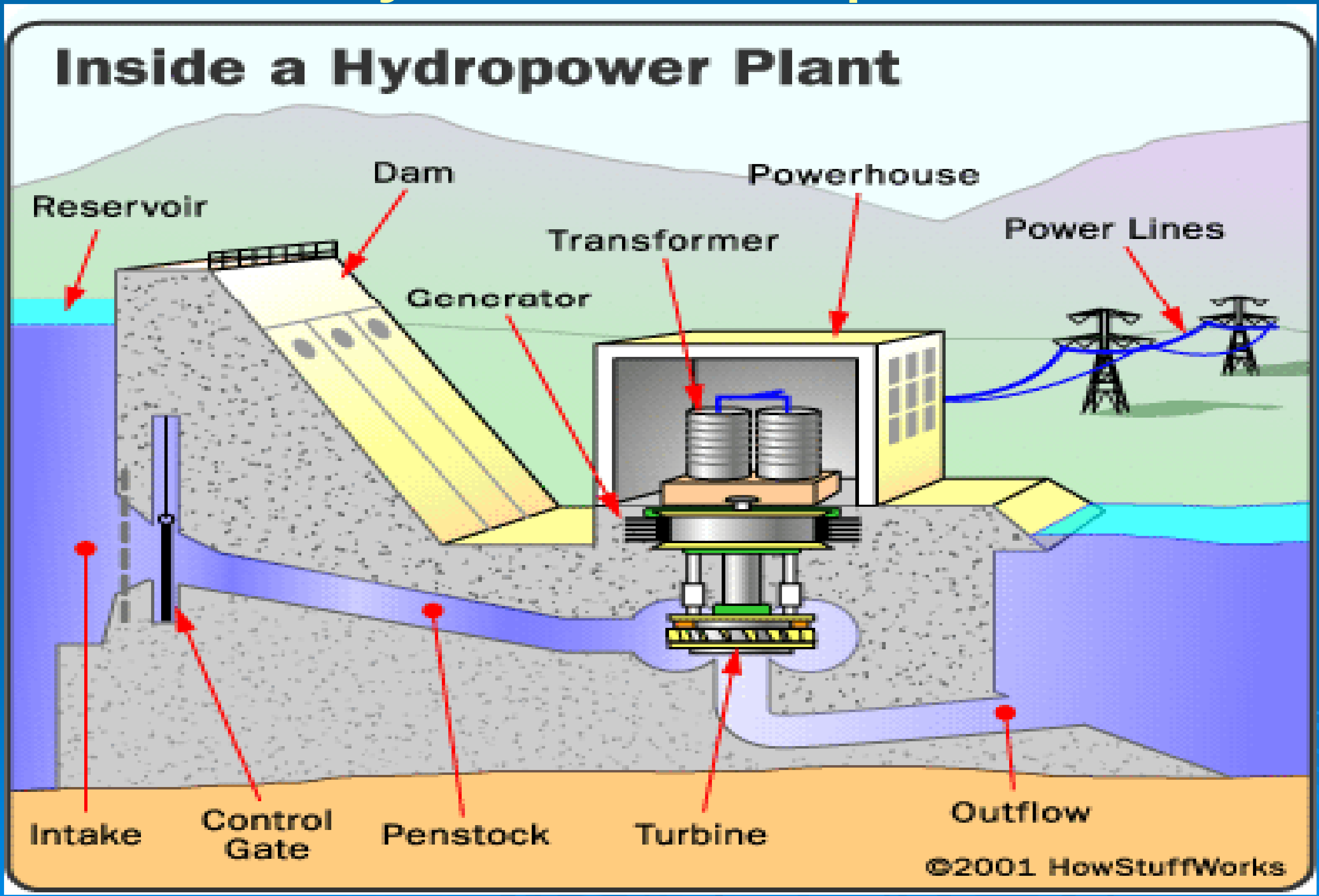
Concerns about Hydropower Development

But like any energy resource, there are environmental and other concerns that must be addressed. These concerns include barriers to upstream and downstream fish passage and changes to water quality, habitat condition, or the flow rate of water moving downstream. Inundation, relocation of people and villages, and the preservation of cultural heritage are also significant concerns when developing large storage projects.

Types of Hydropower Plants

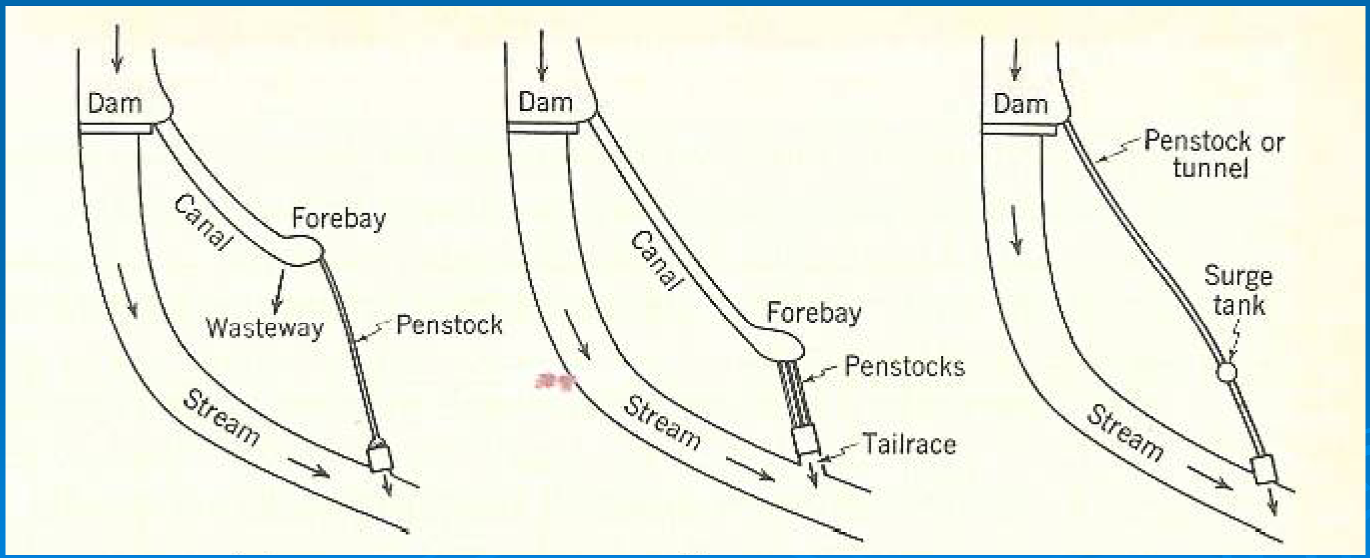
- **Run-of-river**
  no usable storage; power is function of flow. There may be a small amount of storage (called **Pondage**) available with daily fluctuations to allow peaking power production. Requires adequate flow year around. Can be utilized on navigation projects, diversion dams for irrigation, and canals and pipelines for delivery to irrigation projects or water supply.
- **Storage**
  multi-purpose; have seasonal regulation capability
- **Re-regulating (after-bay)**
  receives fluctuating Q from u.s. large hydro peaking plant and releases d.s. in smooth pattern
- **Pumped Storage** (offstream or instream “pump-back”)
  convert low value off-peak energy to high value on-peak energy by pumping at night/weekends and generating at peak hours.

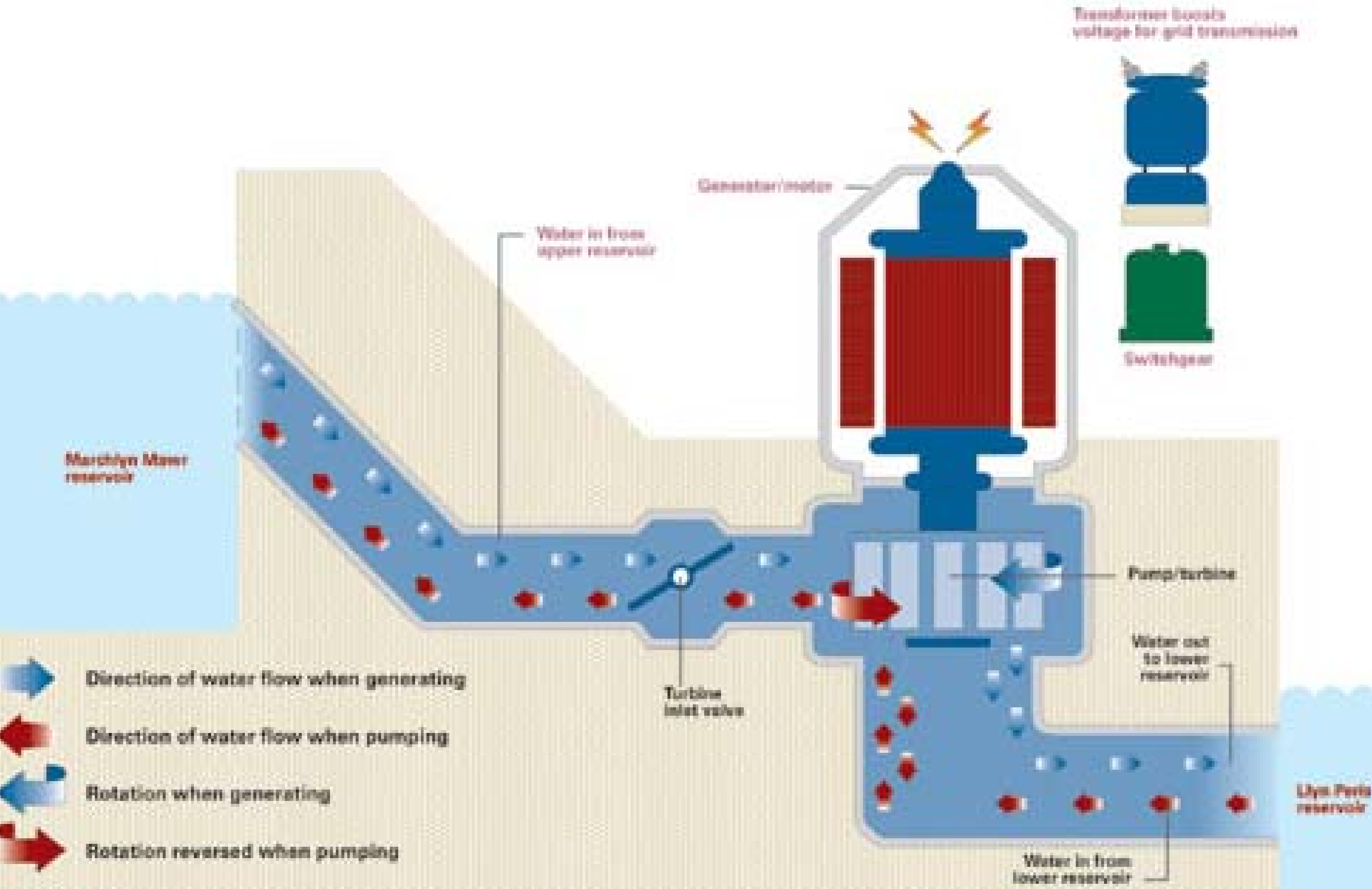
Typical layout of a "concentrated fall" hydroelectric plant



Divided-fall developments

Water is carried to the powerhouse at a considerable distance from the dam through a canal, tunnel, or penstock. With favorable topography it is possible to realize a high head even with a low dam. With this arrangement, head variations in the reservoir may be small compared with the total head, and the turbine can operate near optimum head (peak efficiency) at all times.




Pump/turbine
Turbine inlet valve
Water out to lower reservoir
Water in from lower reservoir
Direction of water flow when generating
Direction of water flow when pumping
Rotation when generating
Rotation reversed when pumping

Pump Storage – Dinorwig (Wales) Power Station

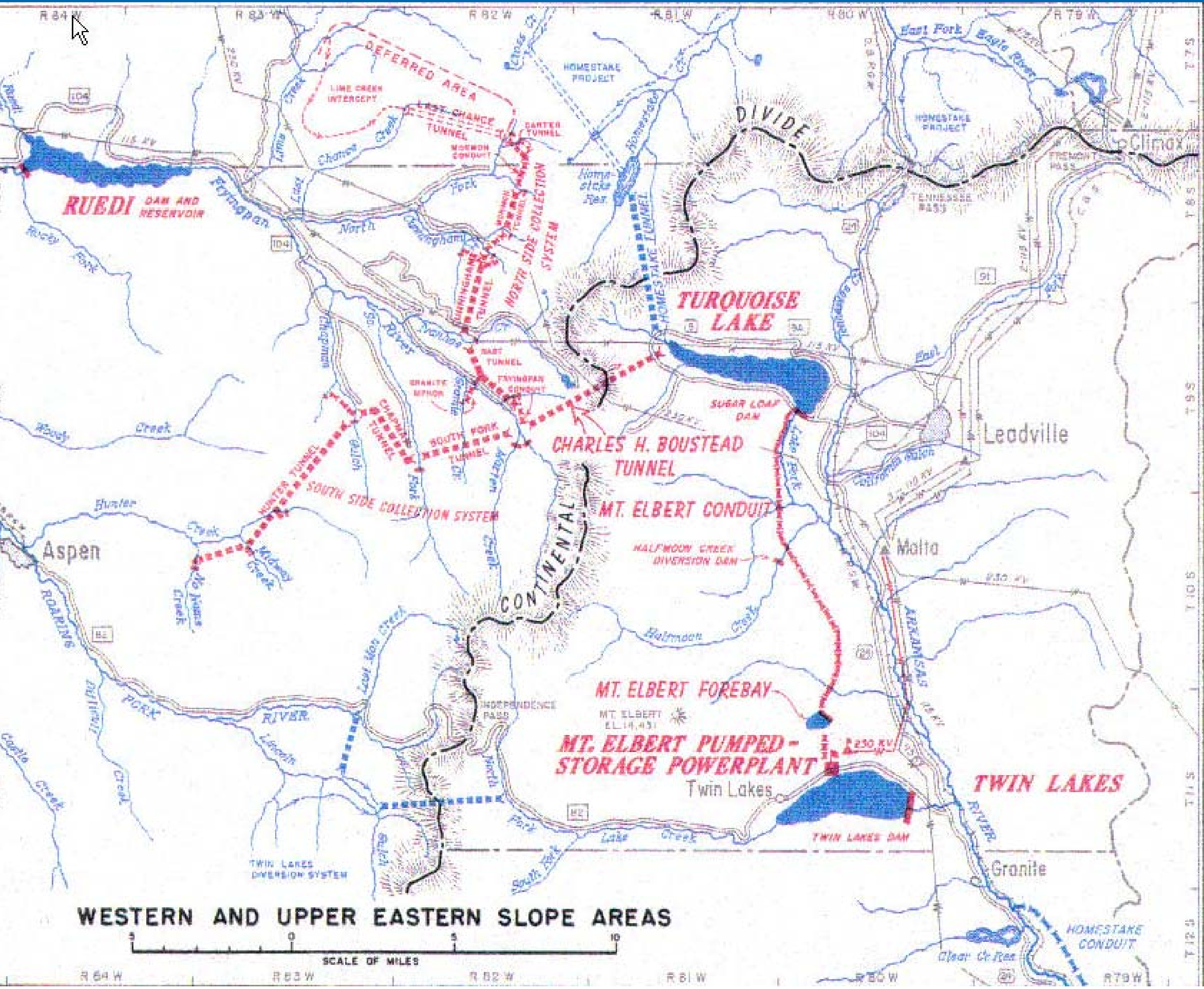
"one of the world's most imaginative engineering and environmental projects"

- Dinorwig is comprised of 16km of underground tunnels, deep below Elidir mountain.
- The station's six powerful generating units stand in Europe's largest man-made cavern. Adjacent to this lies the main inlet valve chamber housing the plant that regulates the flow of water through the turbines.
- Dinorwig's reversible pump/turbines are capable of reaching maximum generation in less than 16 seconds. Using off-peak electricity the six units are reversed as pumps to transport water from the lower reservoir, back to Marchlyn Mawr. Dinorwig has the fastest "response time" of any pumped storage plant in the world - it can provide 1320 MegaWatts in 12 seconds.

Dinorwig Pump Storage Facility

Sept 9, 2008

Mt. Elbert Pumped Storage PP



- Fryingpan-Arkansas Project
- Moves 69,000 AF water from western slope (Roaring Fork) to the Arknasas Basin on Eastern Slope.
- 450 ft drop
- Generates 200,000 KW
- 2-138,000 HP generators (170,000 HP pumps)

Estimating Energy Potential

The power (in terms of electrical output) that can be produced by a hydro plant during a specified time interval can be computed using the power equ:

$$kW = \frac{QHe}{11.81}$$

Where: *Q* is the turbine discharge (flow available during the timestep)

H is the net head

e is the plant efficiency

Gross head is the difference between the u.s. and d.s. water surface elevations.

Net head is the actual head available for power generation, accounting for head losses due to intake structures, penstocks and outlet works.

For planning purposes, the head losses and plant efficiency can be combined. An overall efficiency of .6 to .7 is typically used. Hence $kW = 0.06\ QH_g$ (for overall e_p = .7) can be used.

To convert the power output to energy, this equation must be integrated over time, where both Q and H vary with time.

$$KWH = 0.06\int Q(t)H(t)dt$$

Note that Tailwater varies with Q and headwater is a function of storage.

Hydropower Terms

Avg annual energy: estimate of avg amount of energy that could be generated by a hydro project in a year, based on emination of a long period of historical streamflows.

Firm (primary) energy: energy that can be produced on an assured basis. This is the energy that can be produced through the critical period in the historical streamflow record.

Secondary energy: generated in excess of firm output; interruptible but available > 50% of time.

(Installed) Capacity: maximum power that plant can deliver at any given time.

Dependable (firm) capacity: capacity that the plant can contribute to peak power demands

Hydraulic capacity: max flow that plant can use for power generation. (varies with head and is maximum at rated head).

Plant factor: ratio of average energy (over some period) to installed capacity.

For example:

$$\text{annual plant factor} = \frac{\text{average annual energy}}{(8760\text{ h})(\text{installed capacity})}$$

Example of Daily Plant Factor (Load Factor)

$$\text{Plant Factor} = \frac{(1{,}200\text{ MWh})}{(24\text{ hrs})(100\text{ MW})} = 50\%$$

energy = 1,200 MWh

time = 24 hours

capacity = 100 Megawatts

55

Estimating Firm Energy

Three Basic approaches for determining energy potential of a proposed hydropower site:

1. Flow-duration curve method – uses flow-duration curve of historic streamflows to develop a power-duration curve. H varies only with Q. Good for run-of-river projects
2. Sequential streamflow routing (linear reservoir routing) – manual method for modeling storage, outflow and power generation. This is required for storage projects.
3. Simulation – automates the modeling process.

Flow Duration Method

Typically firm energy is considered as the energy that can be delivered 90-97% of time. Hence, it is based on flow that is equalled or exceeded 90-97% of time.

EXAMPLE (Mays and Tung, Hydrosystems Engineering and Management, p.283-5)

A run-of-river hydro plant is proposed at the Little Weiser River near Indian River, ID. The head available at the site is 30ft and the plant efficiency is about 0.70. Determine the firm energy that can be expected.

For 1 cfs of flow passing through the proposed plant, Power is $kW = 0.06\ QH_g$ = 1.778kW/cfs

Using a monthly timestep (appropriate for firm energy planning studies) and using AF/mo units:

1 AF/mo will produce 21.502 kWH

Flow Duration Method – Example cont'd (Mays and Tung)

The monthly flow duration data is given by the figure.

The firm yield of the basin is 283 AF. Hence the firm energy is

283 x 21.502 = 6085 KWH

The secondary energy is energy that can be provided at least 50% of the time. The 50% exceedance value is 2800 AF/MO. Hence the energy that can be delivered at least 50% of the time is

2800 x 21.502 = 60,206 KWH

The secondary energy is the energy in addition to the firm energy that can be delivered at least half the time.

Secondary energy =
60,206 – 6,085 = 54,121 KWH

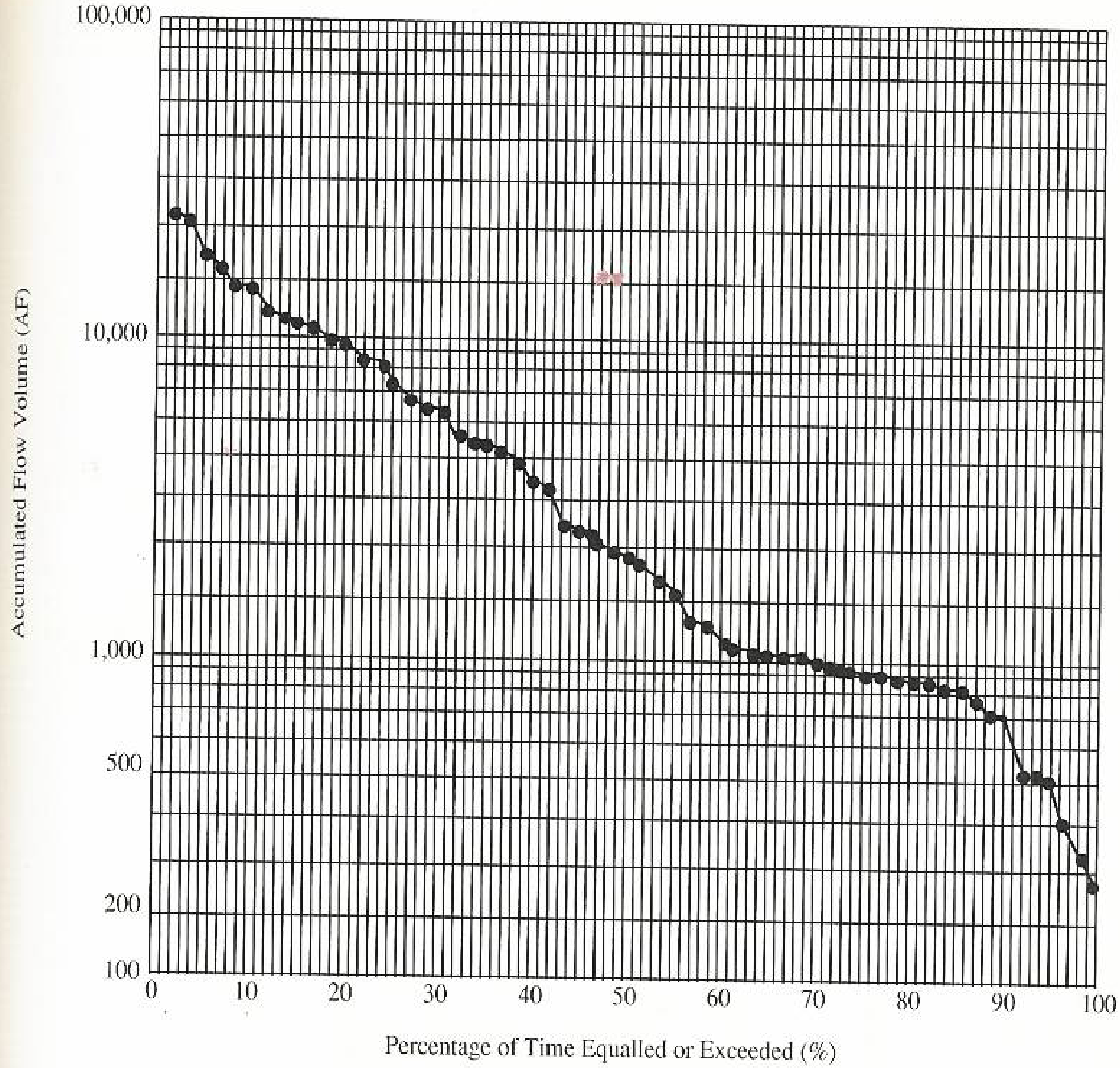


FIGURE 7.2.1
Flow-duration curve for the Little Weiser River near Indian Valley, Idaho (1966–1970).

Estimate Firm Energy

Sequential Routing Method: Like linear reservoir routing, i.e., it is "simulation" in a sequential spreadsheet-like fashion. This can be complex if you have to model the operations over a range of reservoir storages.

But firm energy is based on critical period.

Possible assumptions:

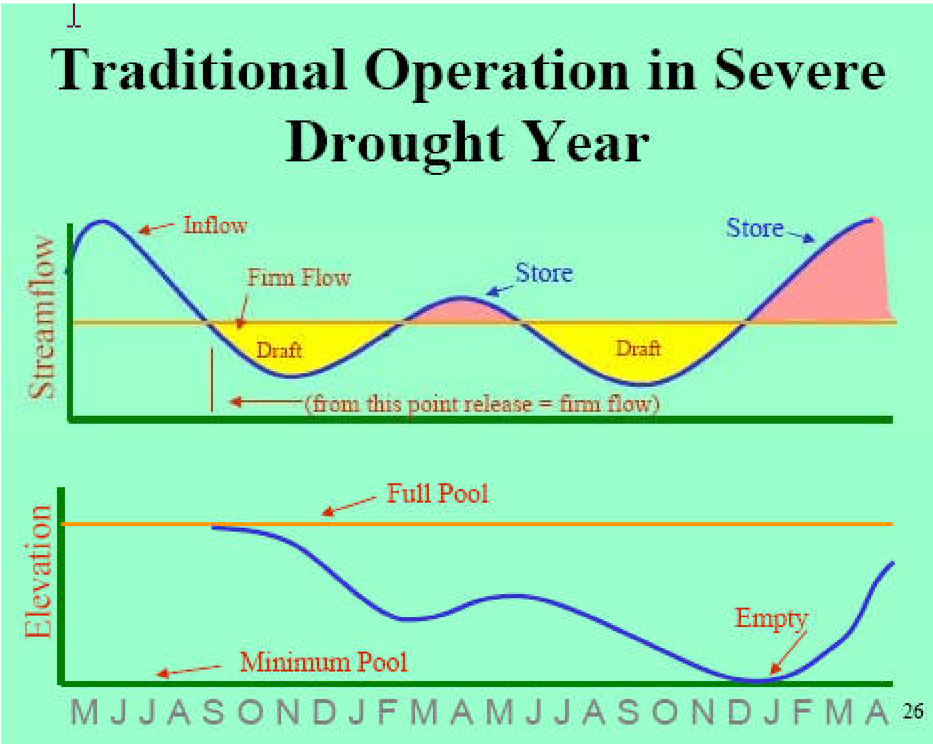
Consider a critical drawdown period (reservoir full to minimum to full again)

Project demands and releases
Assume constant TW elevation H=f(storage)
otherwise H = f(storage, Q)

Note that by considering critical period, you don't have to consider flood flows.

S(t) = S(t-1) + Inflow – Outflow – Losses
Outflow = Firm Flow (design firm draft or yield)
Energy(t) = eff/11.81 * Outflow * H(Storage) * dt
Firm Energy = minumum Energy from this computation

Can calculate firm energy for various storage
Capacities and reliabilities.



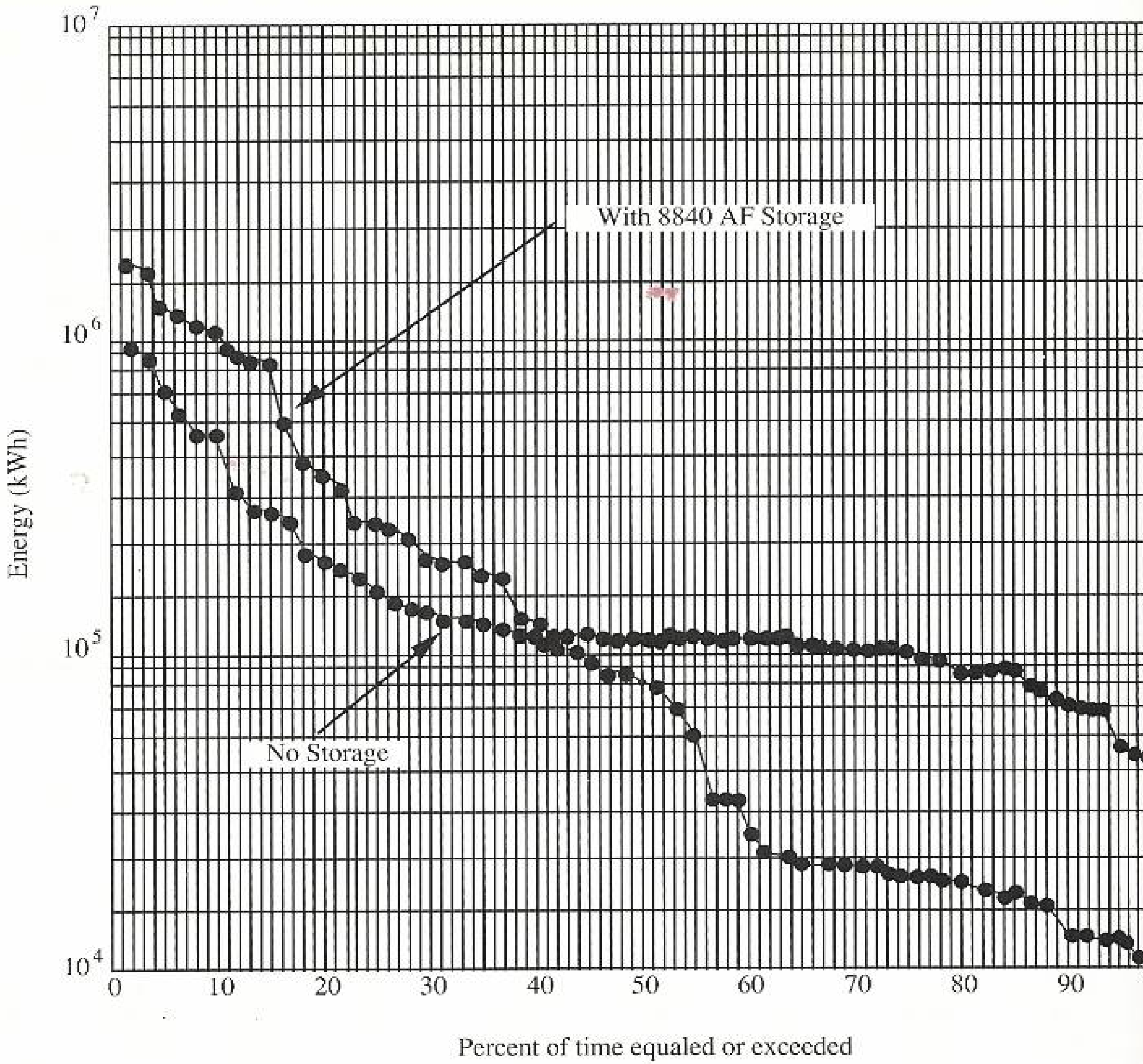


FIGURE 7.3.1
Energy-duration curves for Little Weiser River.

Need to consider Hydropower Operations and Economics

Load: demand for electricity, as average or capacity (peak) demand

For planning:

capacity demand – expected maximum annual peak load

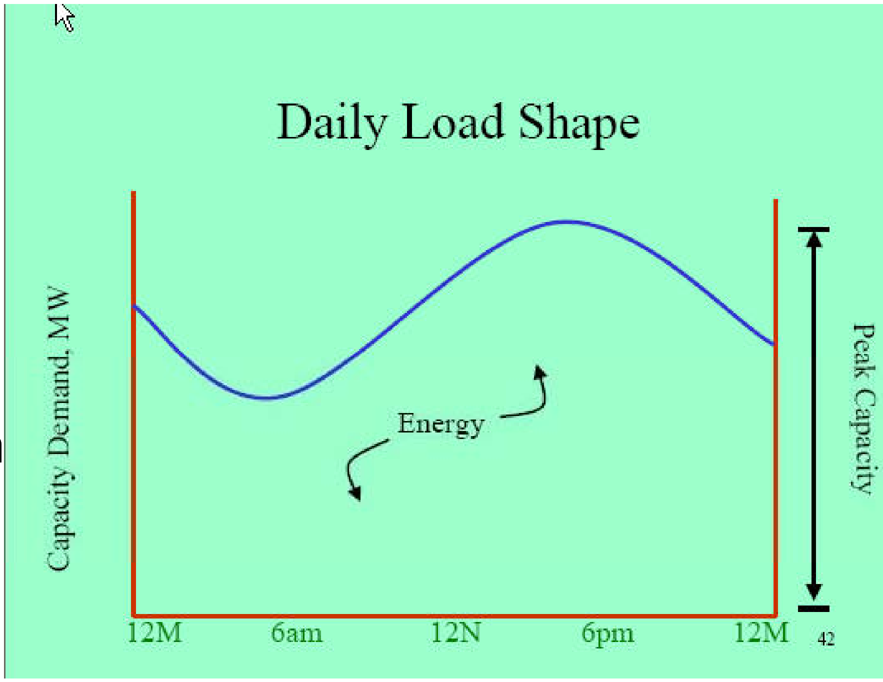
energy demand – average annual energy requirement

Load factor: ratio of avg load to peak load over some period (daily, weekly, monthly or yearly)

$$\text{Daily load factor} = \frac{\text{average power demand per day}}{\text{peak power demand per day}}$$

Load factor in an industrial area may be as high as 80% and as low as 30-40% in a residential area.

High load factor → unit cost of power is low b/c system operates near capacity (hence near best efficiency) most of the time. If load factor is low, the generating capacity of the system will be idle much of the time

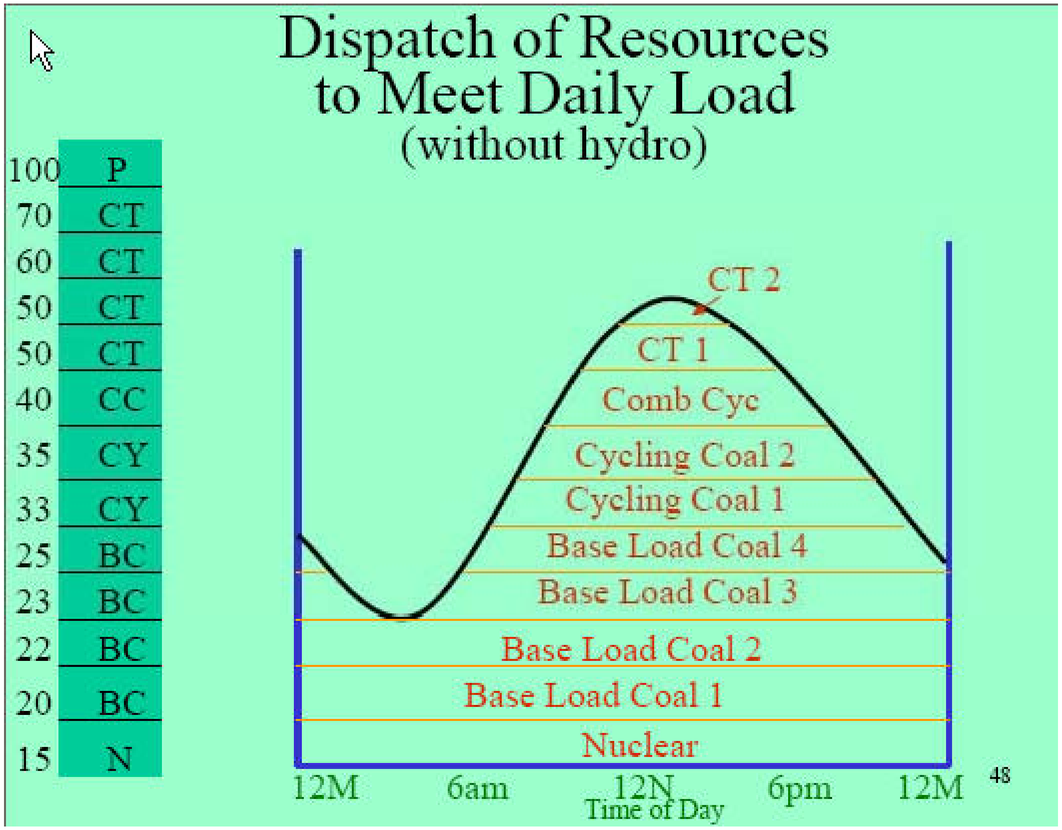


Hydropower Economics

Combined System: a power production system that includes both hydropower and thermal power (gas, coal, oil, nuclear). In the thermal system (without hydro) the combination of sources to meet the load are selected based on the value of the power being produced and the ability to turn the units on and off.

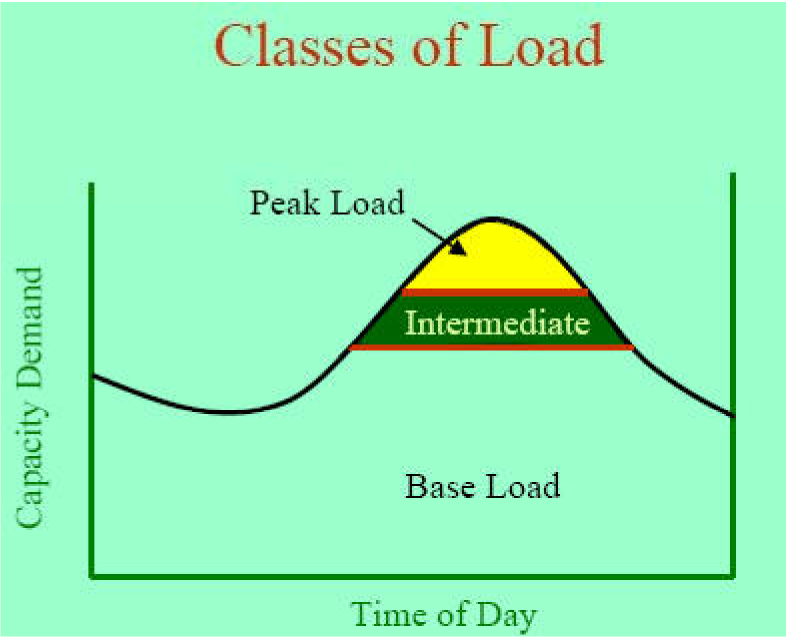
Resources Available to Meet Loads (without hydro)

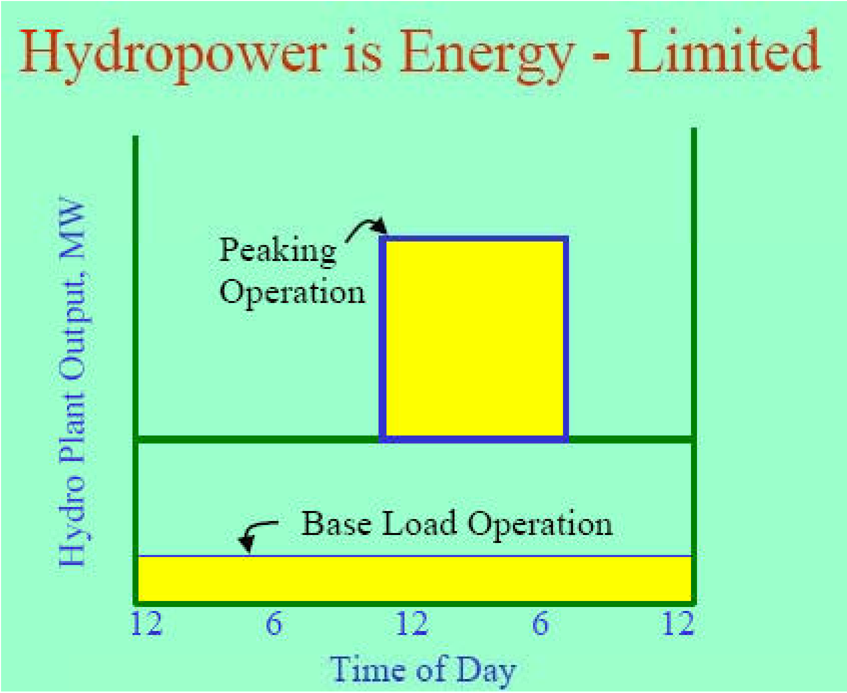
Nuclear	15 \$/MWh
Base-Load coal	20-25 \$/MWh
Cycling coal	25-30 \$/MWh
Combined cycle (gas)	35 \$/MWh
Combustion turbine (gas)	50 \$/MWh
Combustion turbine (oil)	70 \$/MWh
Purchases	50-200 \$/MWh



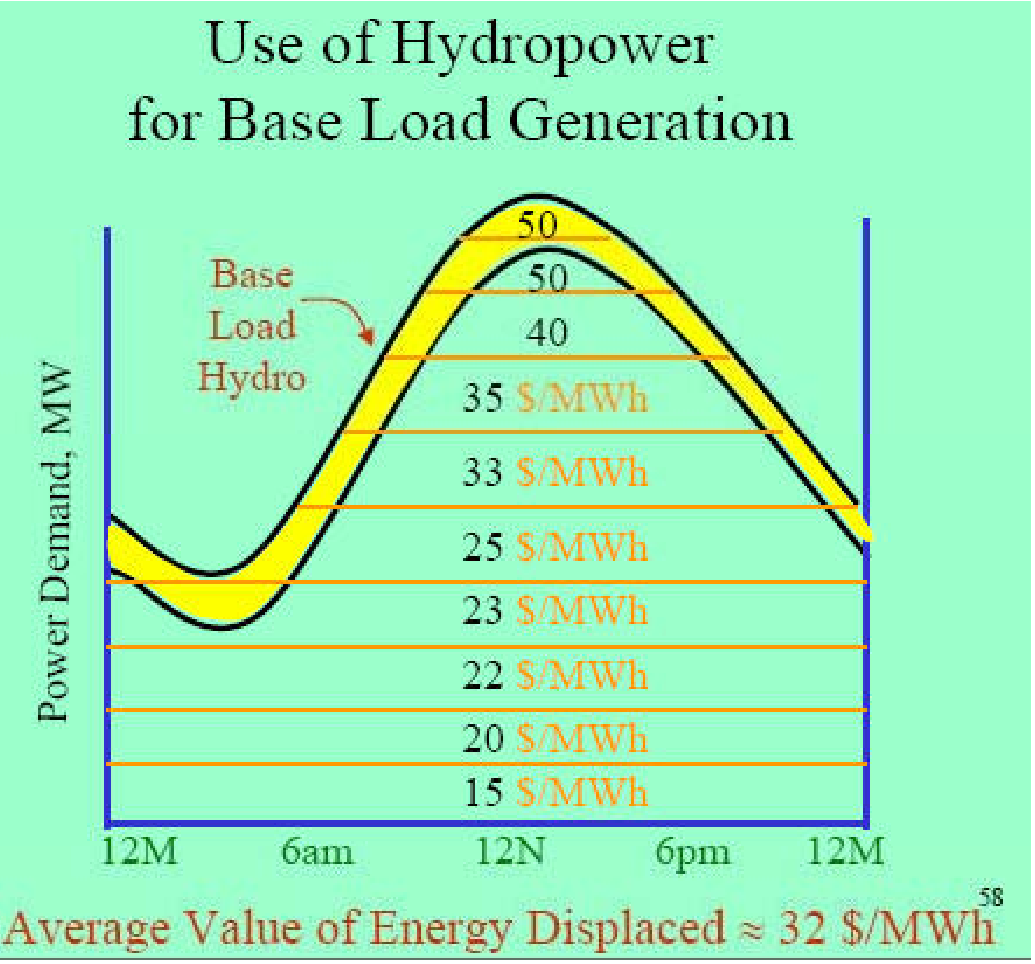
Hydropower Economics

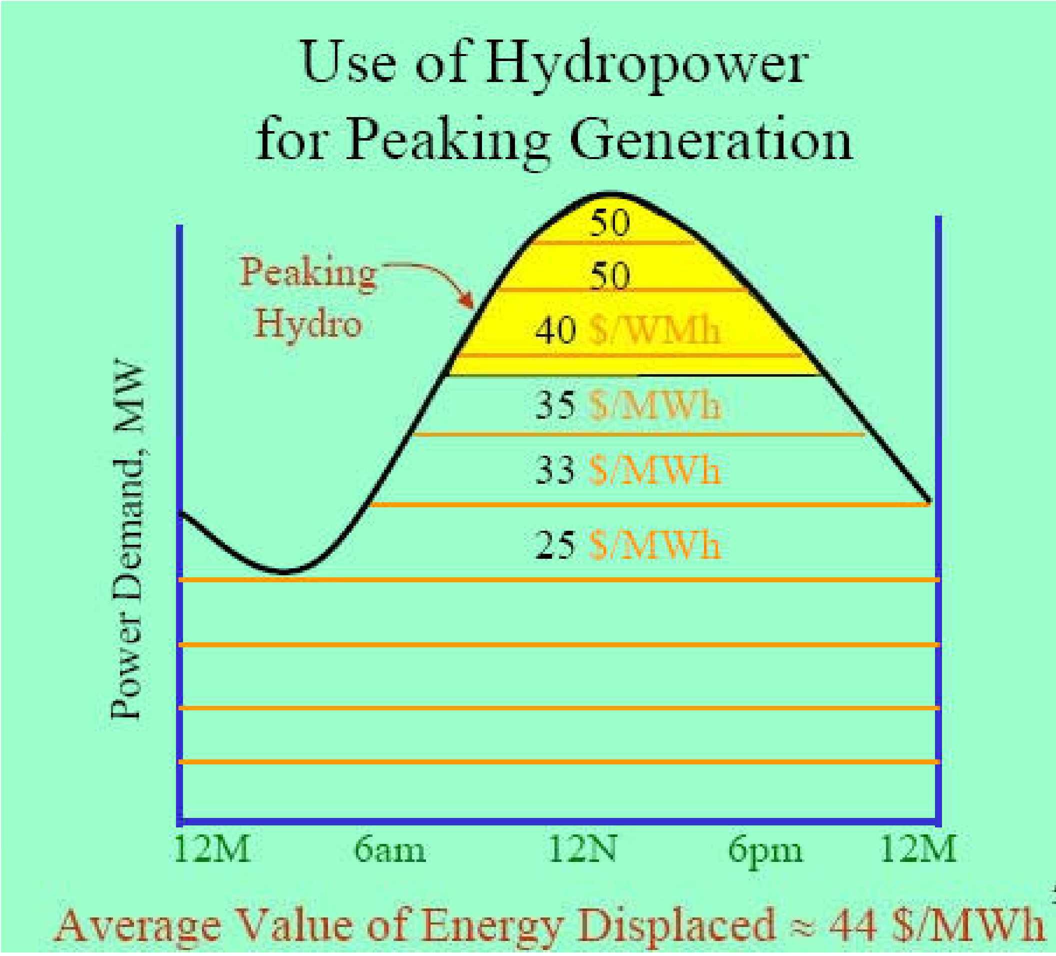
Hence the value of energy produced by the hydropower plant varies with the type of use. Hydropower can be turned on and off easily and quickly, and the cost of producing it is very low. But hydro is (often) the least available. So the most economical use of it is for peaking power where it replaces the the most expensive units of thermal energy. The value of hydropower is in the avoidance cost of producing thermal energy.





Hydropower Economics





Hydropower Economics

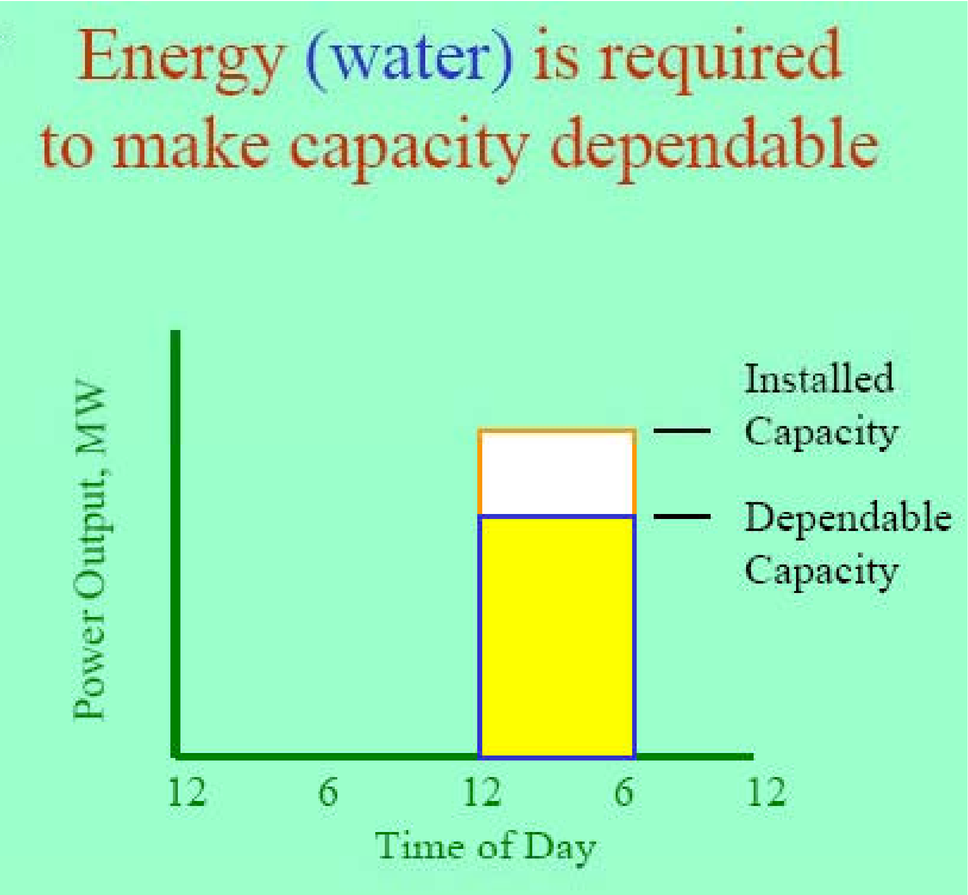
Thus, hydropower cannot be produced just anytime water happens to be released for other purposes. The benefits of hydropower depend on having an energy-producing capacity that can be used as needed in conjunction with the other sources of energy.

Dependable Capacity

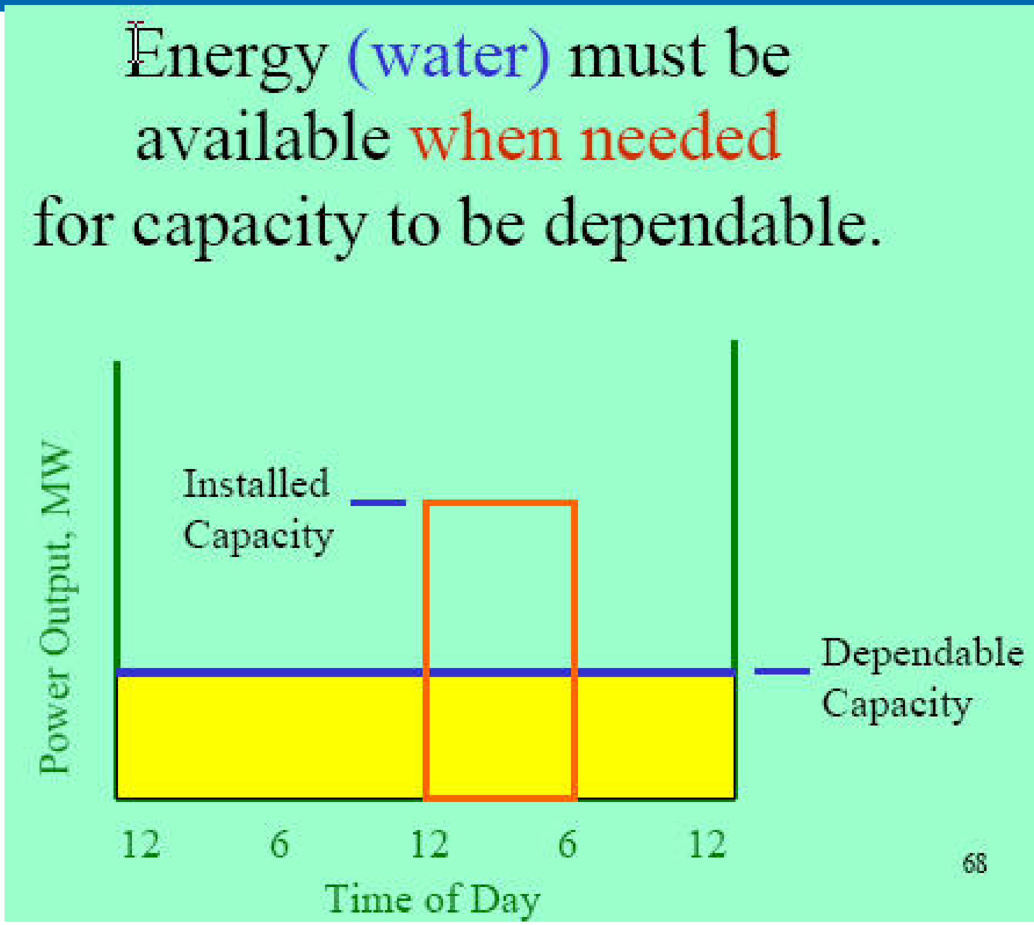
The load-carrying capability of a plant or system

- under adverse conditions
- for the time interval and period specified
- when related to the characteristics of the load

Hydropower Economics



The installed capacity is too great for the amount of water available to produce power. The dependable capacity is less than the installed capacity.



Here the amount of water is adequate to produce the total energy, but the timing is not adequate – cannot produce the power needed for peaking capacity.

Firm Energy Revisited

Firm Power has 2 Components:

Energy, MWh

Capacity, MW

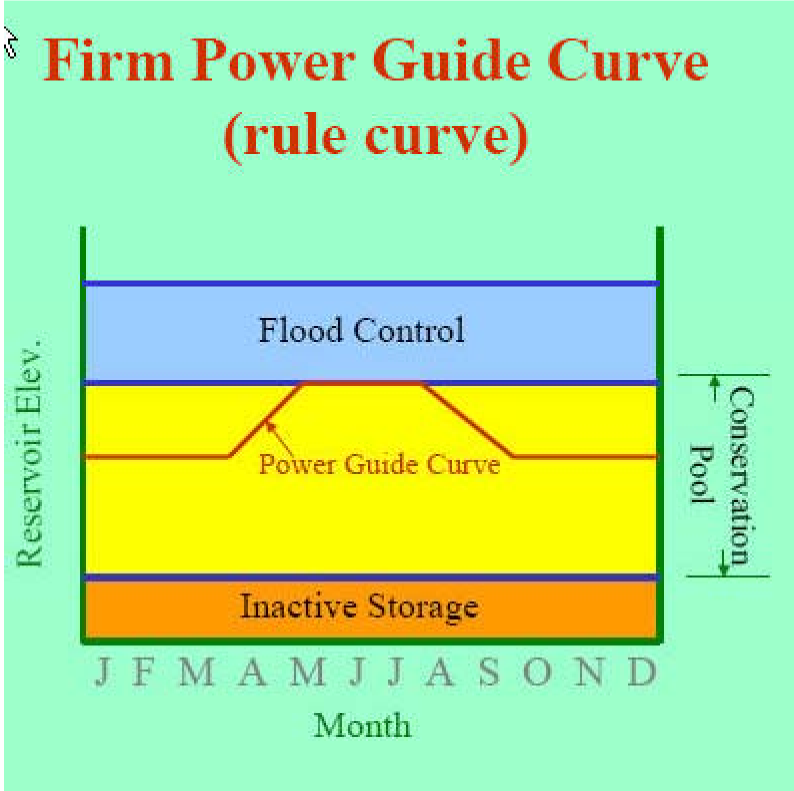
A firm power (energy) planning study must determine

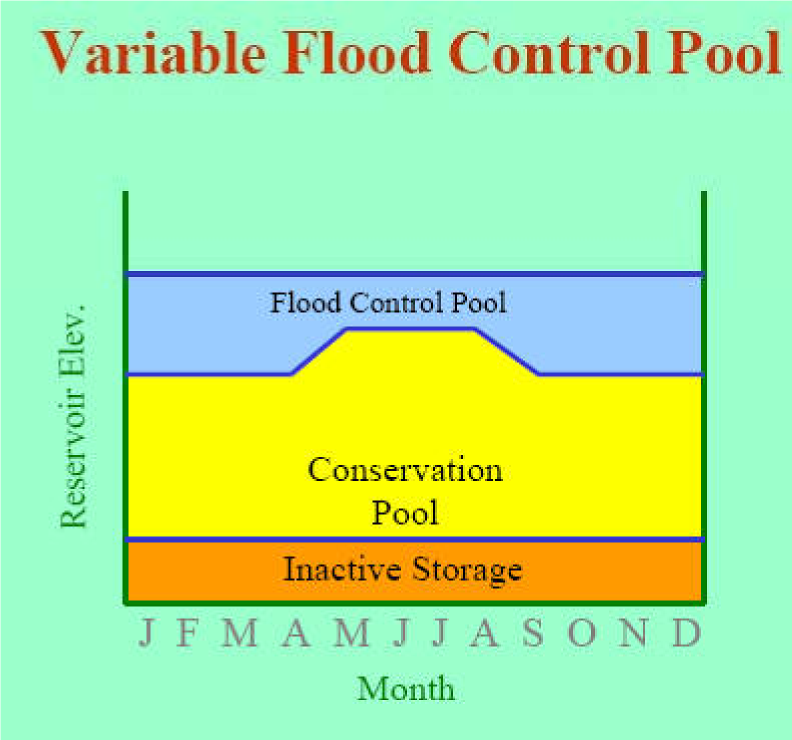
- How much energy can be produced annually with reliability of ~97%.
- The capacity (power) that can be produced by the plant reliably.

This analysis requires simulation tools that can model the water and water processes (storage, losses, tailwater, etc.) and the hydropower production (capacity and efficiency, varying heads, peaking power)

Operating Rules for Hydropower

Hydropower guide curves provide for flexibility of operations in the conservation pool to meet higher power demands at certain times of the year.

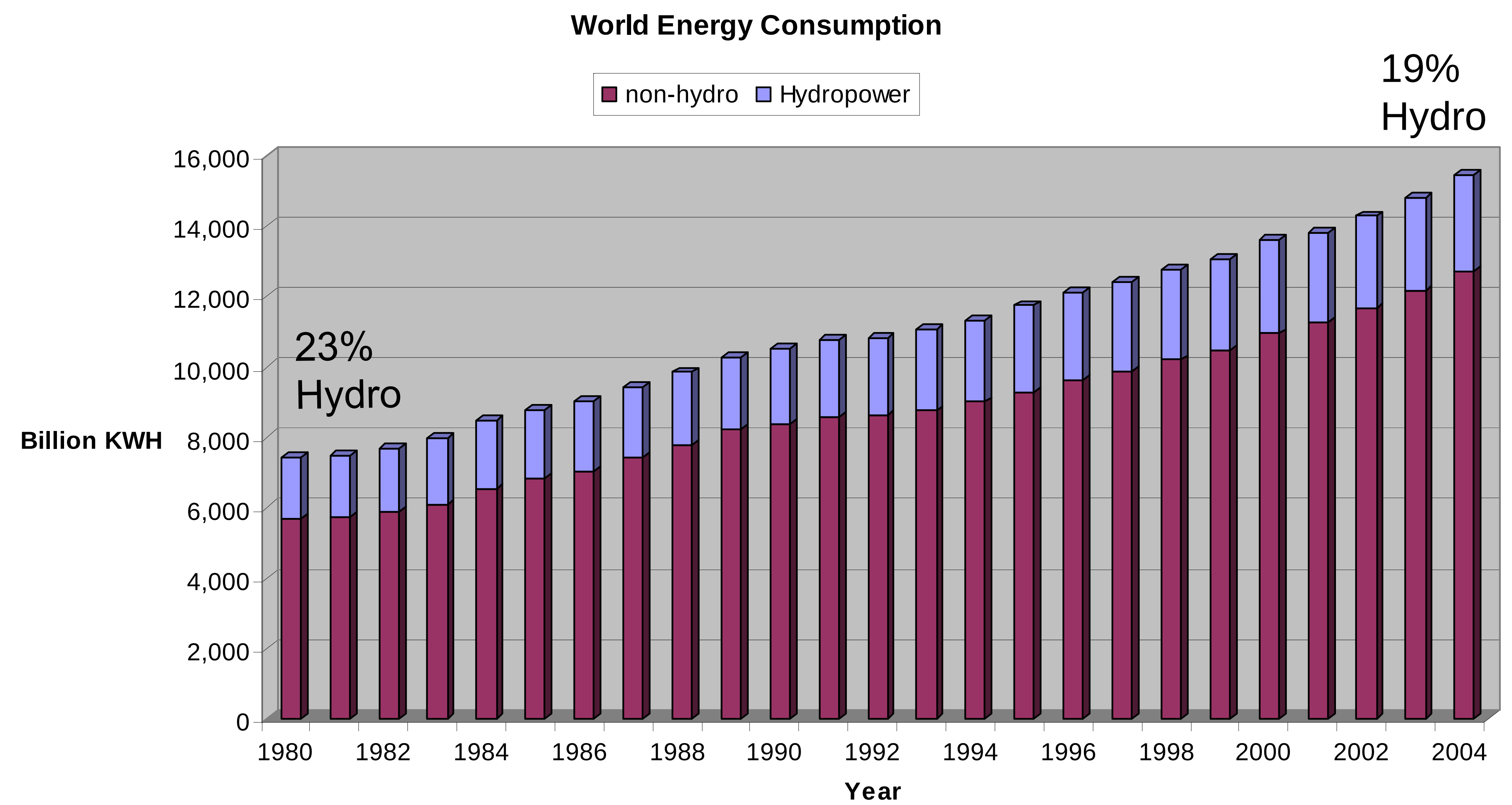




FERC Relicensing

All hydropower plants are subject to licensing by FERC. Many plants are now being relicensed. They must consider the multiple objectives of the projects, including environmental flows and recreation.

Itaipú Dam, Paraguay/Brazil. The world's largest hydroelectric facility.
Credit: Itaipu Binacional


World Energy Consumption
non-hydro
Hydropower
19%
Hydro
23%
Hydro
Billion KWH
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1980
1982
1984
1986
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Year