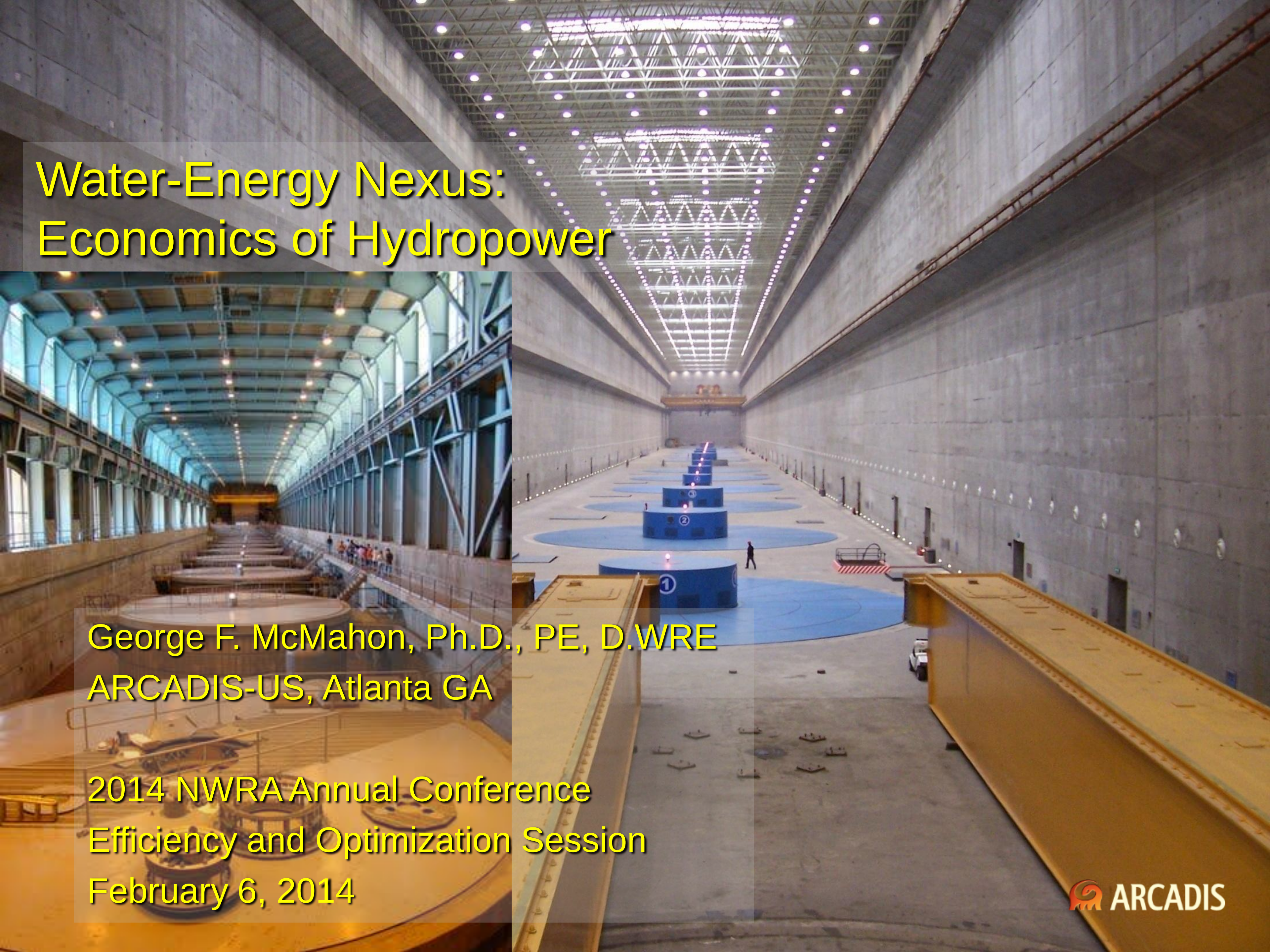

Water-Energy Nexus: Economics of Hydropower

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ARCADIS-US, Atlanta GA

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Efficiency and Optimization Session
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Topics

- Hydropower facts, statistics and terminology
- Hydroelectric powerplant components and characteristics
- Economic analysis
  - Development planning
  - Operational planning
  - Federal hydropower
  - Private hydropower

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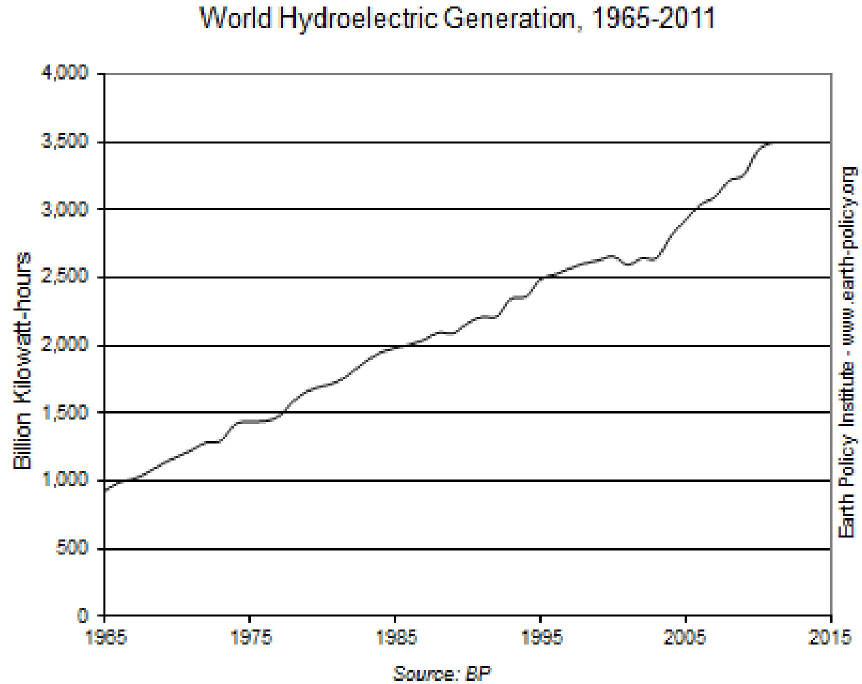
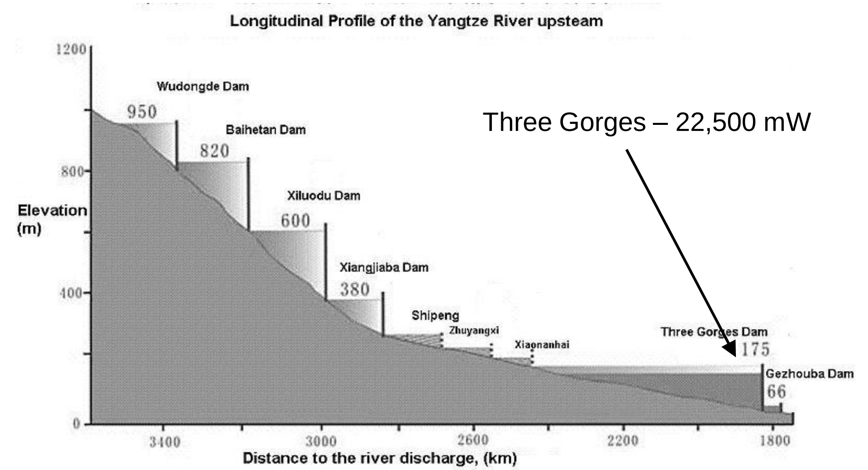
Facts and statistics

- 18 percent (≈3,500 TWh) of global electric energy supply
- 3% growth rate since 1965
- World hydroelectric energy ranking
  - China (300% increase from 2000-2010)
  - Canada
  - Brazil
  - U.S.
- 6.5 percent (≈290 TWh) of U.S. generation
- 67 percent of total renewable energy generated in U.S.
- First hydroelectric power plant constructed at Niagara Falls in 1879





Terminology

Hydropower – conversion of the potential and kinetic energy of water into electrical energy using a water wheel or hydraulic turbine, connected to a generator

Power – rate of performing work or energy generation, measured in units of capacity (kW or mW)

Energy – work (power x time), measured in kWh or mWh

Head – differential water surface elevation available for power generation, measured in feet or meters

- Gross head – before hydraulic losses
- Net head – after hydraulic losses

Conventional hydro – hydropower facilities used for power generation

Pumped-storage hydro – hydropower facilities used for power generation and pumping (reversible)

Terminology (continued)

Load (mW): Power demand as a function of time

Capacity (mW): Maximum power a plant can deliver at any instant in time, also known as *capability*

Installed capacity (mW): Aggregate nameplate or rated capacity of all units in a plant

Dependable capacity (mW):

- Capacity a plant or system can reliably contribute to the increment of the load to be supplied
- Load-carrying ability of a plant or system
- Alternative (normally thermal) plant capacity displaced by hydro

Firm (primary) energy (mWh) – energy that has assured availability in the increment of load to be supplied, i.e. makes capacity dependable

Hydropower is energy-limited by flow, head and storage

Hydropower installation categories

- Low head
- High head
- Conventional
- Pumped storage

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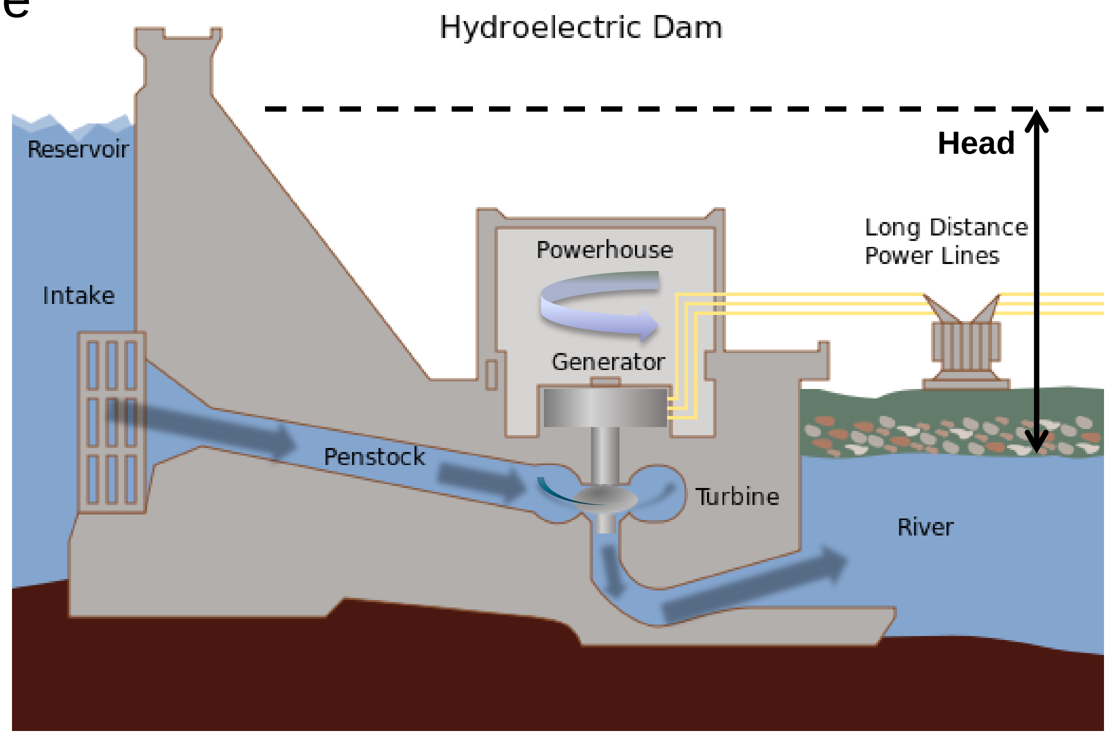
Hydroelectric powerplant components

- Dam
  - Impounds water to create head and storage
- Intake
- Penstock
  - Conveys water under pressure to turbine
- Powerhouse
  - Generator
  - Turbine
  - Scroll case, gates, governor
  - Draft tube
  - Tailrace
- Switchgear



Low-head hydro

Run-of-river projects – little or no usable storage; power output is intermittent, strictly a function of inflow $(Q_{out} = Q_{in})$

- Navigation locks and dams
- Low-head and constant-pool projects

Pondage projects – small amount of usable storage sufficient for daily or weekly flow regulation; peaking or continuous power potential

Reregulation projects – sufficient usable storage for regulation of peaking power releases from upstream storage projects; continuous power potential determined by upstream project operation

- Modulate/stabilize downstream flows
- Afterbay reservoirs for pumped-storage projects

High-head hydro

Storage projects – storage sufficient for seasonal or inter-annual flow regulation; predominantly peaking power projects $(Q_{out} = Q_{in} - \Delta S)$

Pumped-storage projects – sufficient storage and reversible generators to enable conversion of low-value off-peak energy, i.e. nights and weekends, to high-value peaking energy, i.e. weekday hours of peak power demand $(Q_{out} = Q_{in} - \Delta S + Q_{pump})$

- Integral – on-stream
- Non-integral – offstream

Water power equation:

$P\ (kW) = Q_{out} \cdot H \cdot e_t \cdot e_g / 11.81$

where:

Q_{out} = *turbine release (cfs)*

H = *net head (feet)*

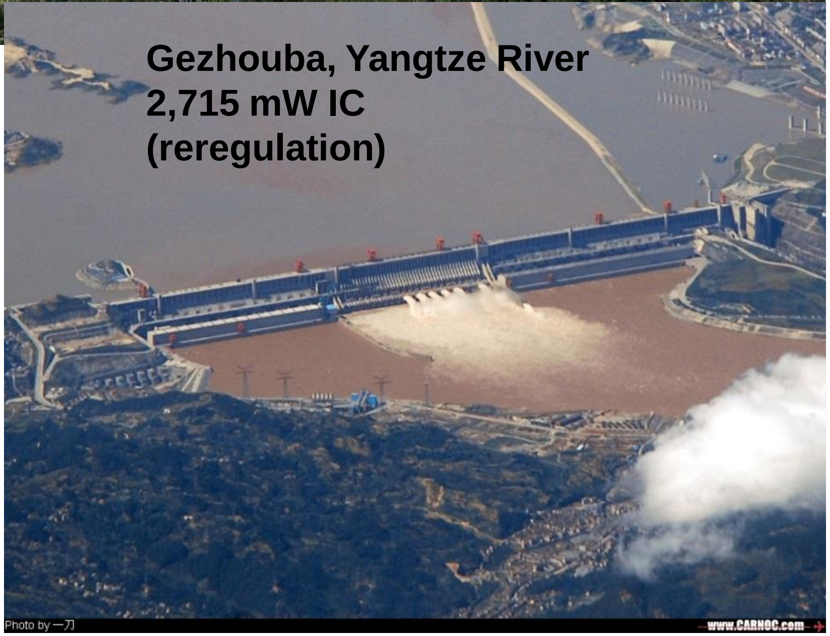
e_t = *turbine efficiency*

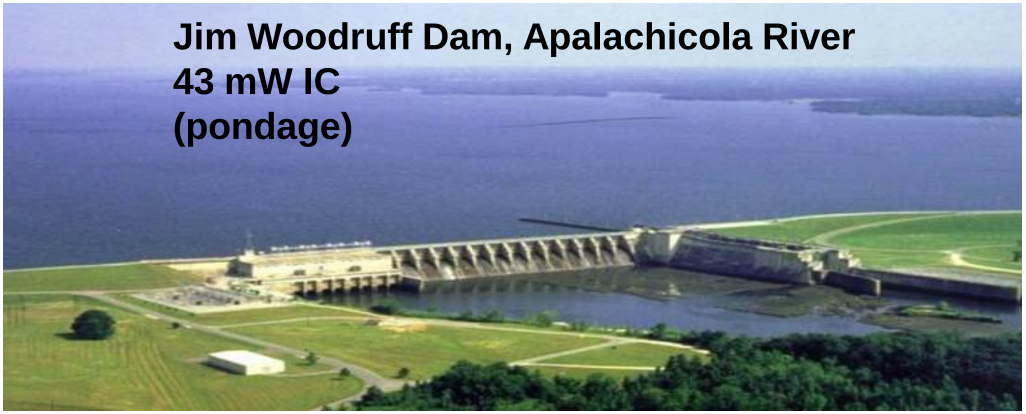
e_g = *generator efficiency*

Conventional hydropower

<u>Generation</u>

- Run-of-river
- Pondage
- Storage
- Reregulation



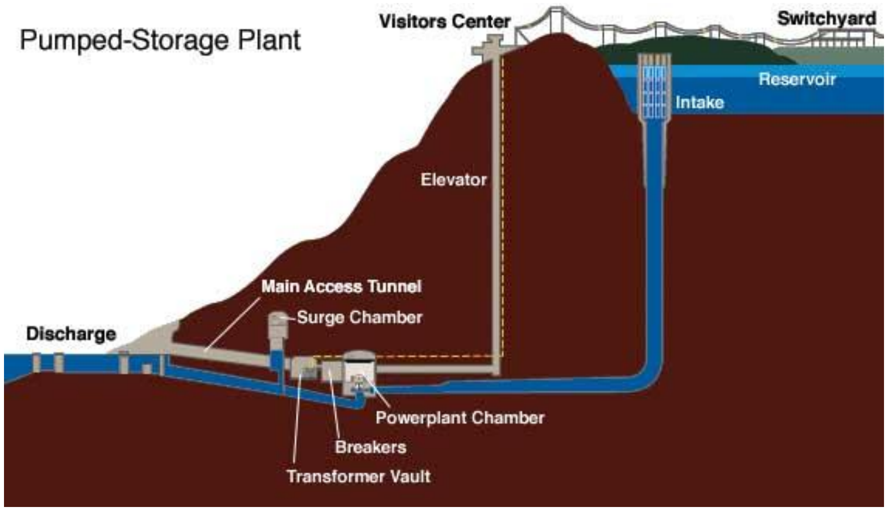


Pumped-storage hydropower

<u>Generation and pumping</u>

- Integral
- Non-integral

Richard B. Russell (USACE)
300 mW conventional capacity
300 mW pumped-storage capacity
(integral)



Raccoon Mountain (TVA)
1,650 mW pumped-storage capacity
(non-integral)

Hydropower economics

- Development planning – feasibility of project development or plant expansion
  - Turbine selection
  - Plant sizing

- Operational planning – operational changes to maximize hydro energy and capacity benefits, subject to non-power constraints
  - Hydropower benefits – avoided costs of alternative resources (energy and capacity)

- Hydro resource analysis
  - Demand (load)
  - Supply (load-carrying ability)

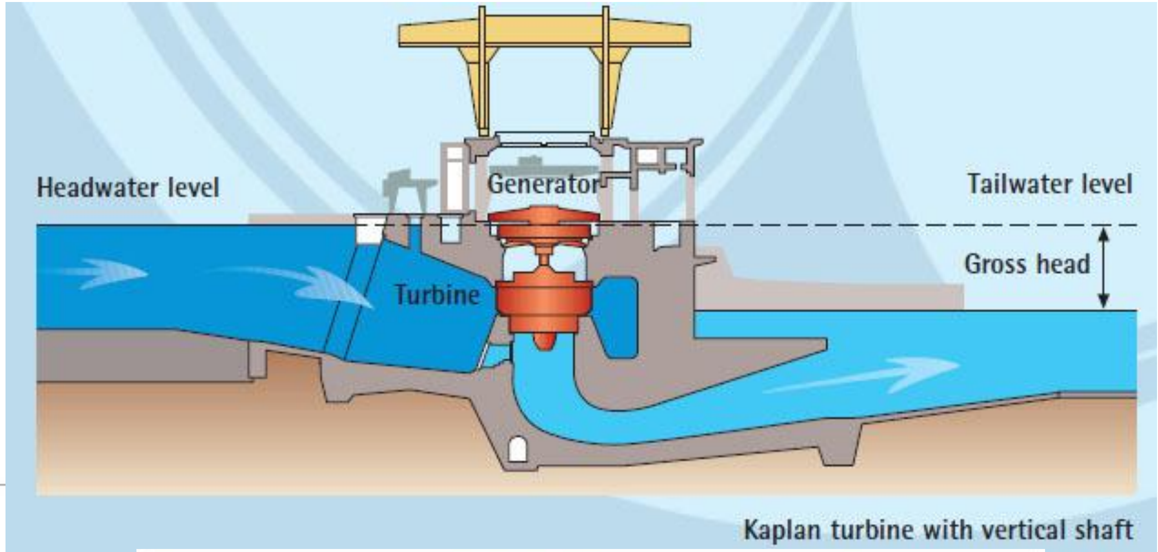
- Feasibility analysis – federal hydropower

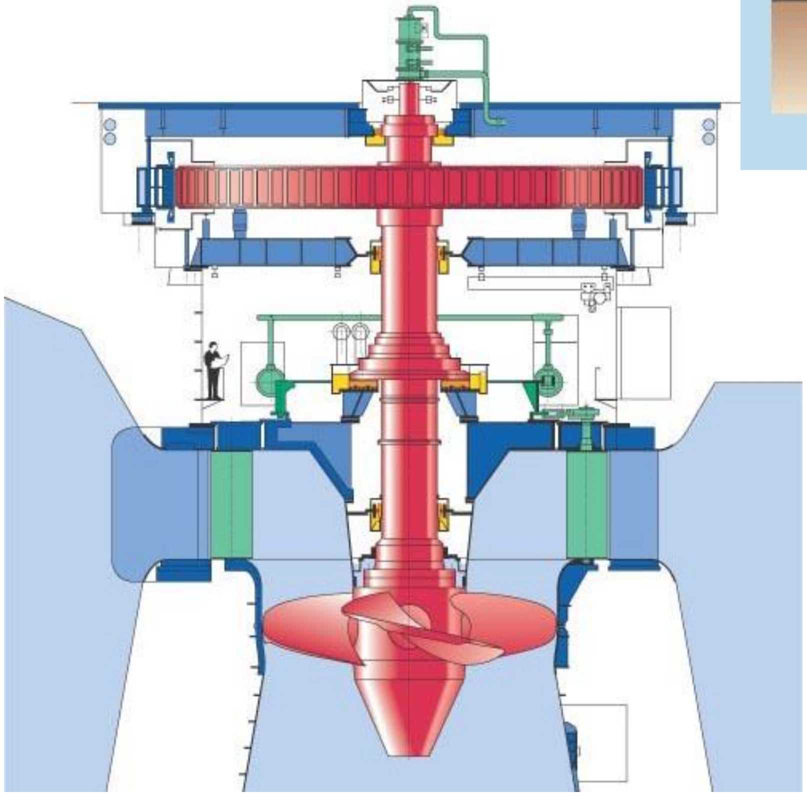
- Feasibility analysis – private hydropower

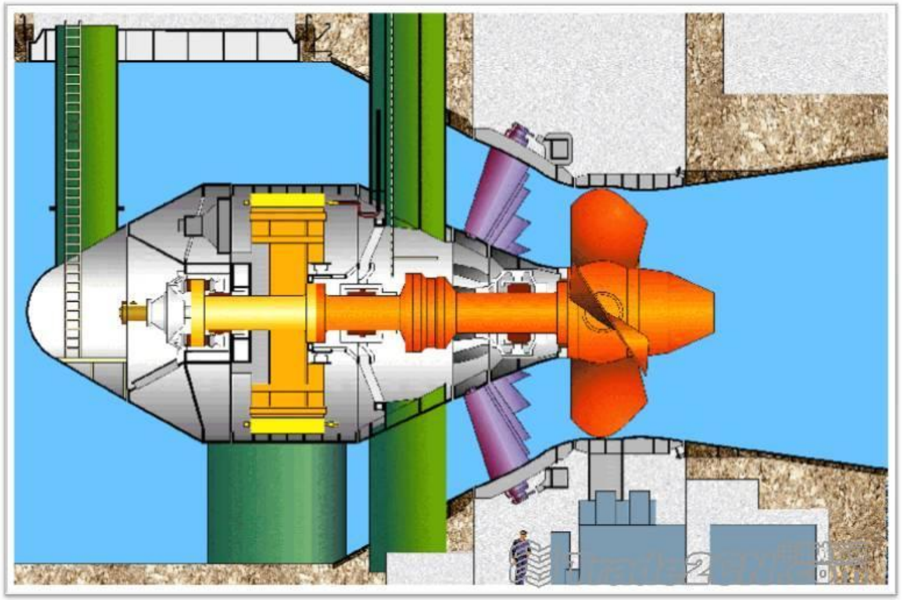
Turbine selection (low head)

Reaction turbines

- Kaplan/propeller: 30-200 feet
- Bulb: 5-100 feet







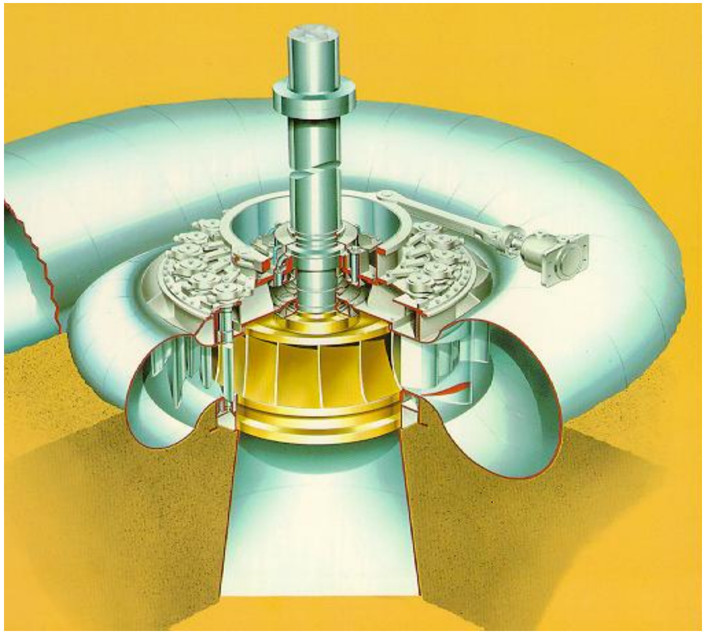
Turbine selection (high head)

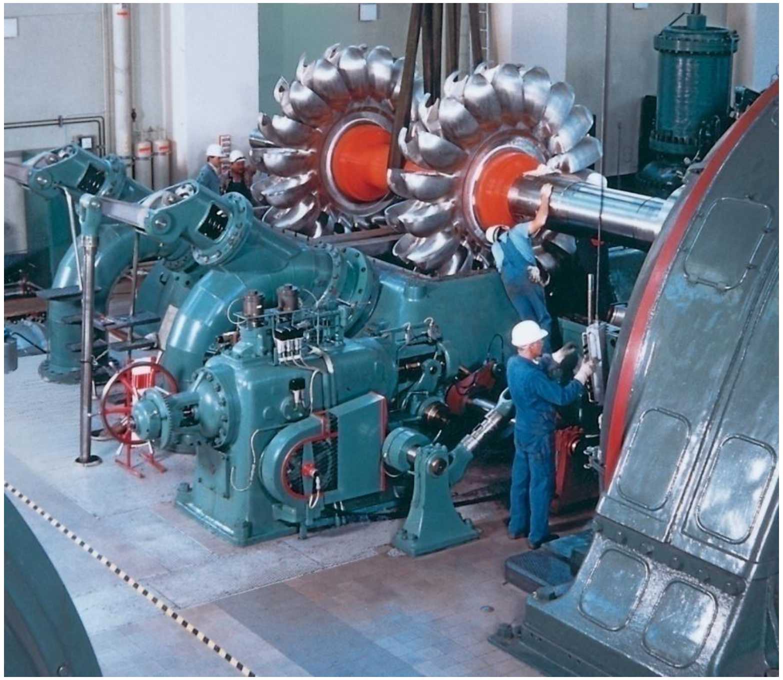
Reaction turbine

- Francis: 30-2,000 feet

Impulse turbine

- Pelton: >1,000 feet

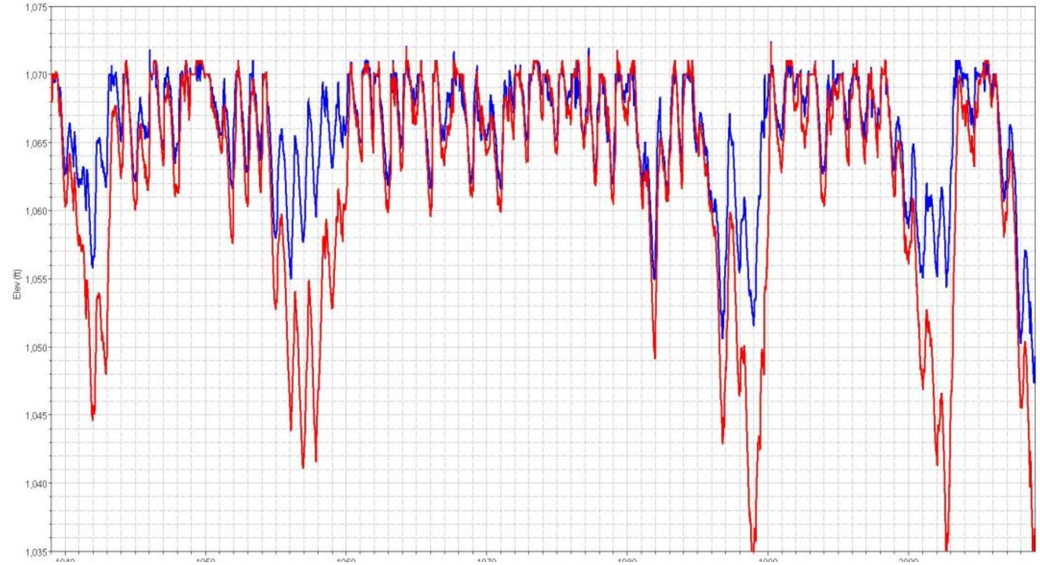


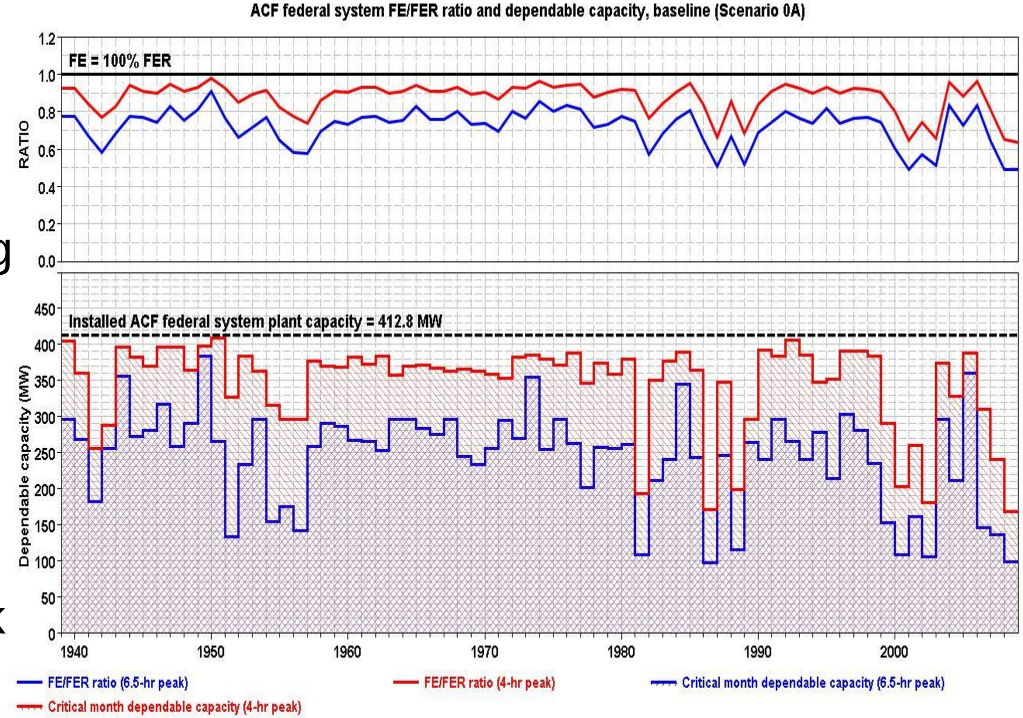


Plant sizing

Estimation of hydro system energy and power potential

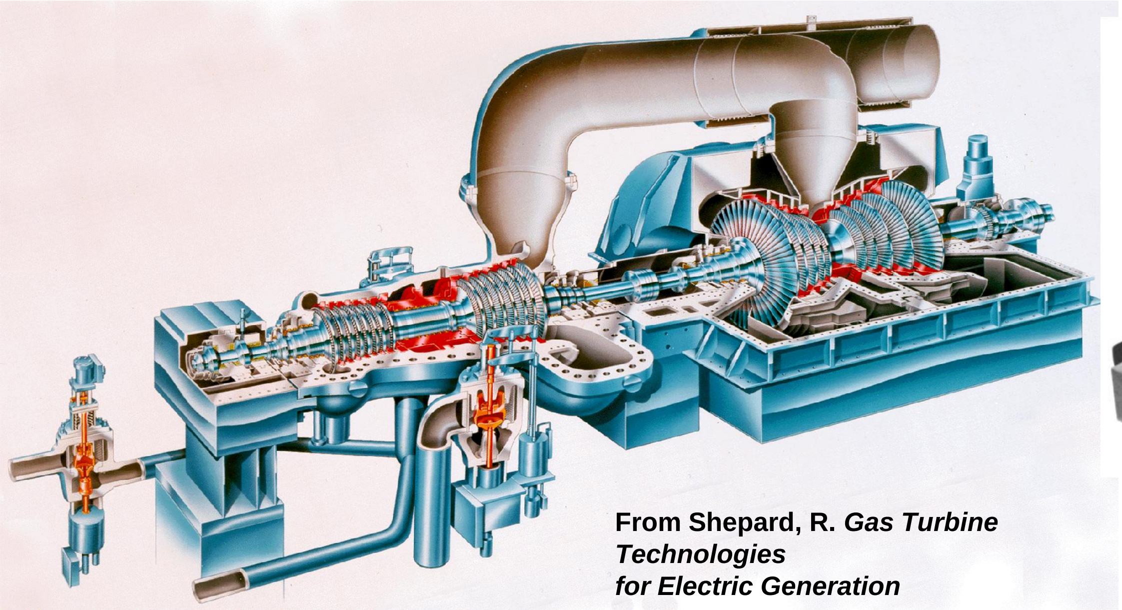
- Run-of-river projects (Q_{in}=Q_{out})
  - Flow-duration analysis
  - Sequential streamflow routing: $kWh = \int Q_{out}(t)H(t)e\,dt/11.81$
  - Plant sizing to maximize average annual energy
- Storage projects and reservoir systems ($Q_{out}=Q_{in}-\Delta S(+Q_{pump})$)
  - Sequential simulation (modeling of alternative plant installations and operating rules)
  - Critical period and dependable capacity determination
  - Storage allocation and plant sizing to maximize firm/on-peak energy generation potential



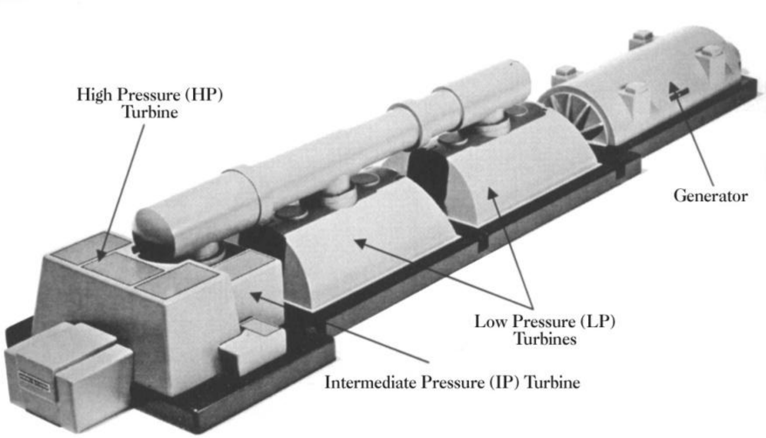


Alternative resources – steam cycle

- Nuclear, coal or oil-fired
- Boiler generates steam
- Slow startup and shutdown
- Operated in base increment of the load
- High capacity replacement cost ($200/kW/yr)
- Efficiency 35-40%
- Low operating cost ($29/mWh)

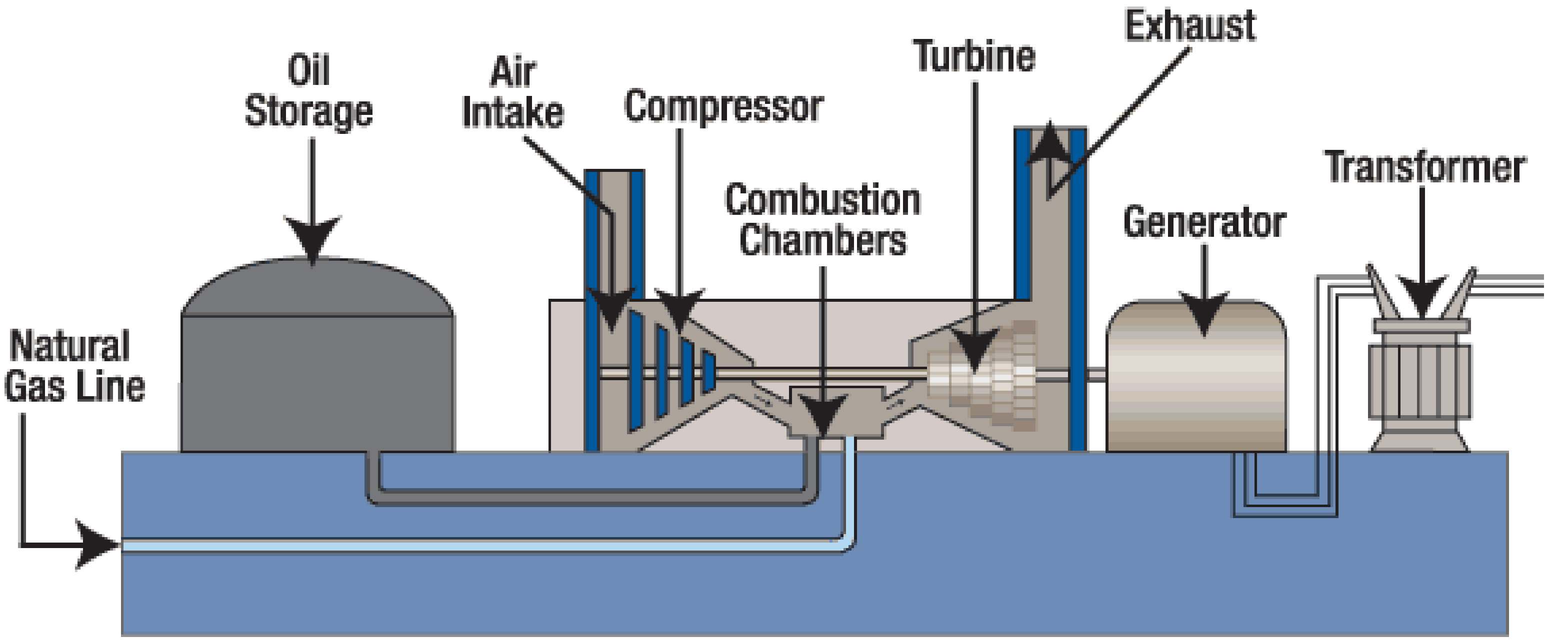


From Shepard, R. *Gas Turbine Technologies for Electric Generation*



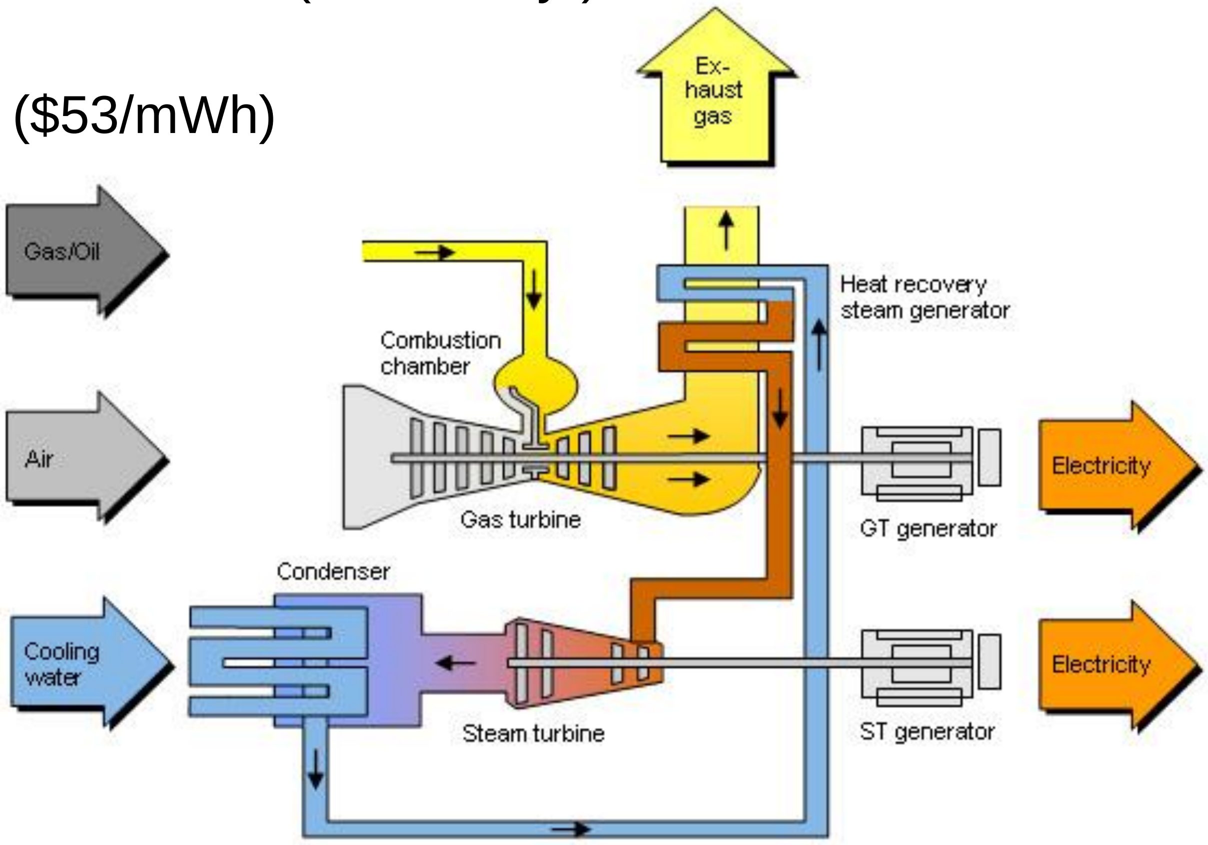
Alternative resources – combustion turbine

- Gas or oil-fueled
- Rapid startup/shutdown
- Primarily operated in peaking increment of the load
- Low capacity replacement cost ($53/kW/yr)
- Efficiency 20-40%
- High operating cost ($95/mWh)



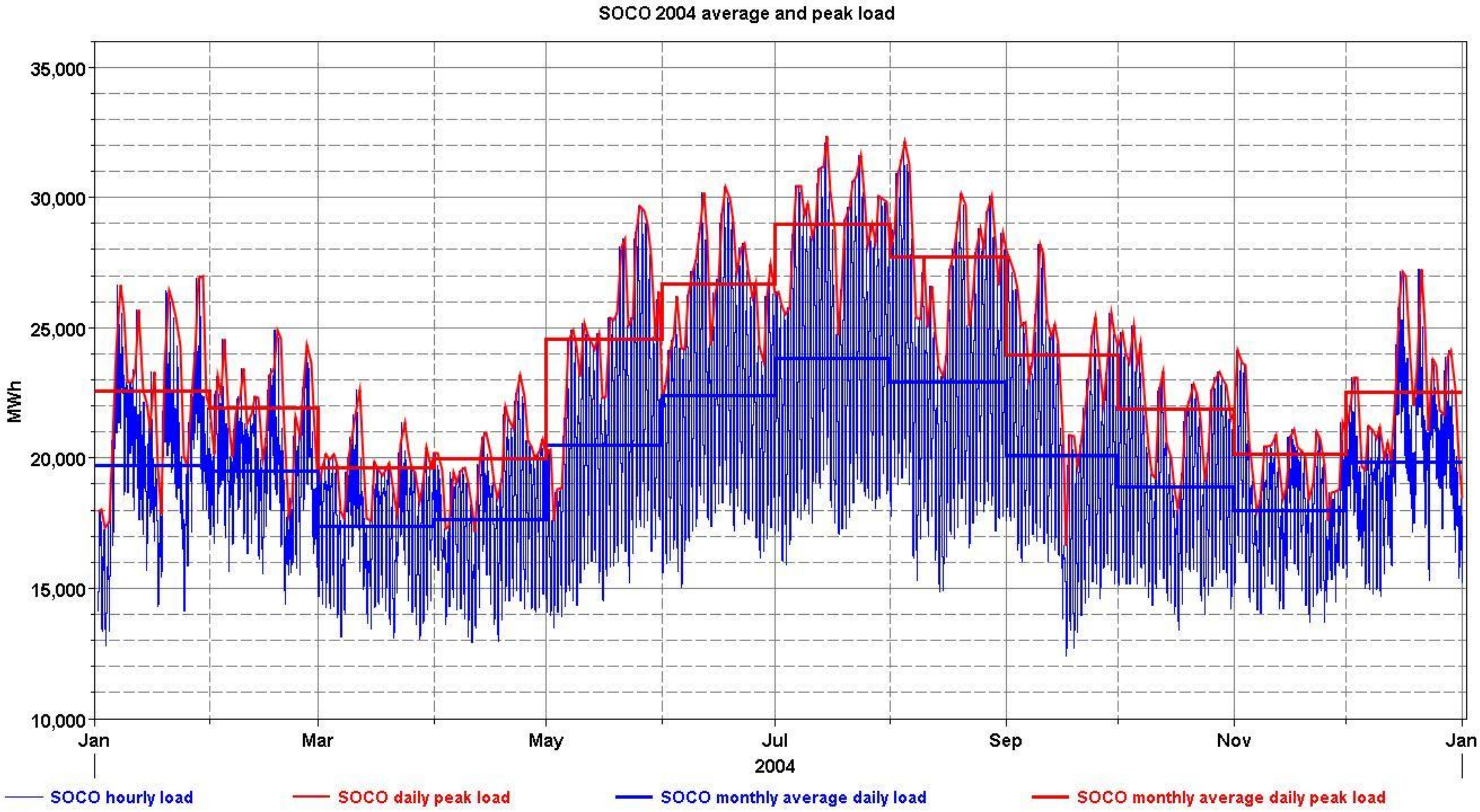
Alternative resources – combined cycle

- Steam generated using combustion turbine exhaust
- Phased startup/shutdown
- Operated in intermediate increment of load
- Medium capacity replacement cost ($121/kW/yr)
- Efficiency 40-50%
- Medium operating cost ($53/mWh)

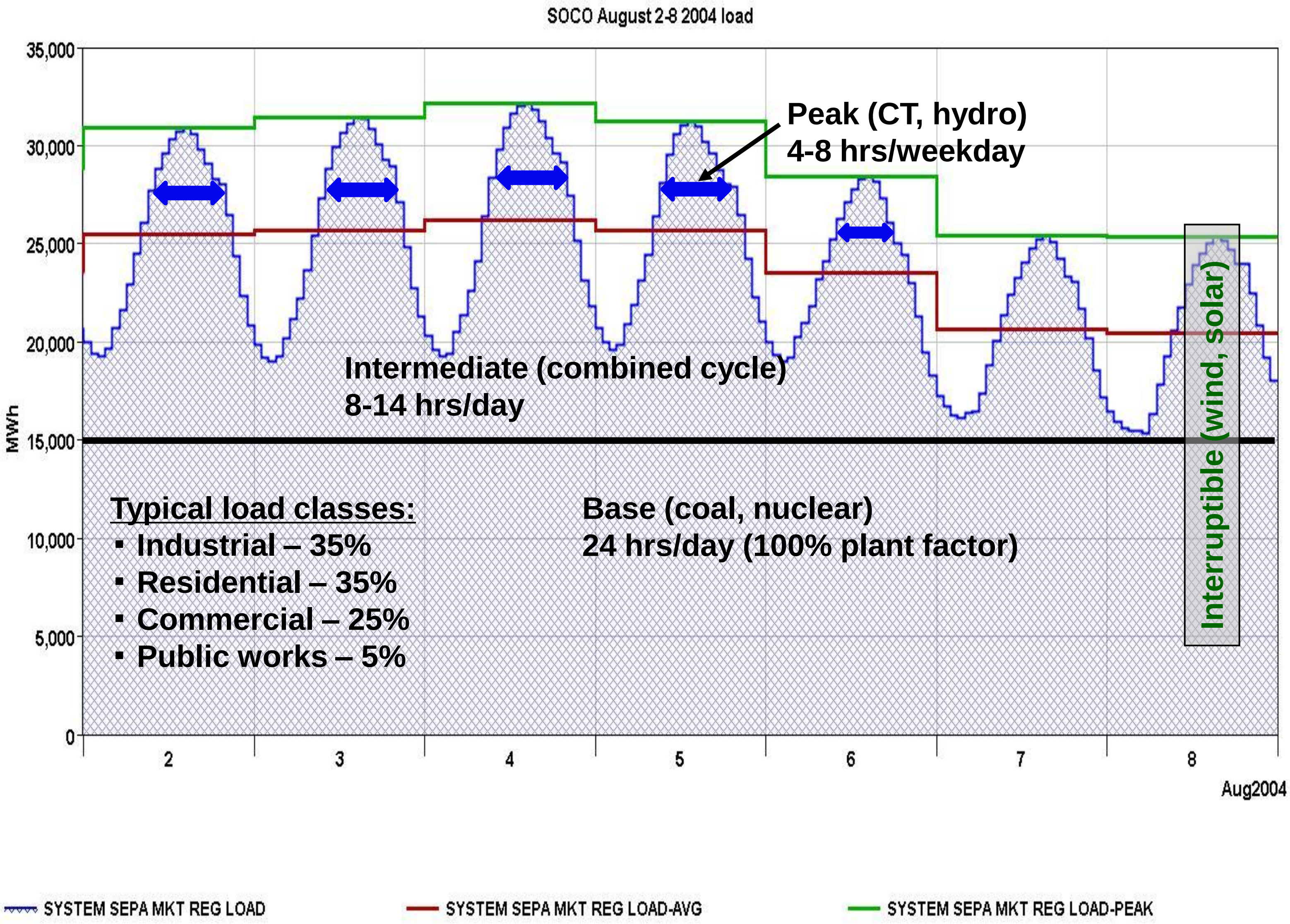


Hydropower resource analysis – demand

Electric system load – power demand; rate at which electric energy from all sources is delivered to the regional power grid



Load increments and load shape



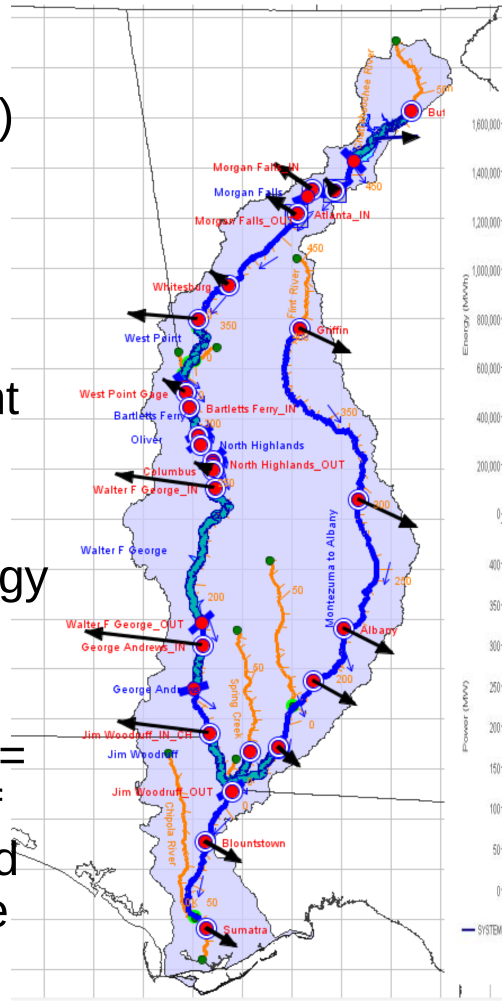
Hydropower resource analysis – supply

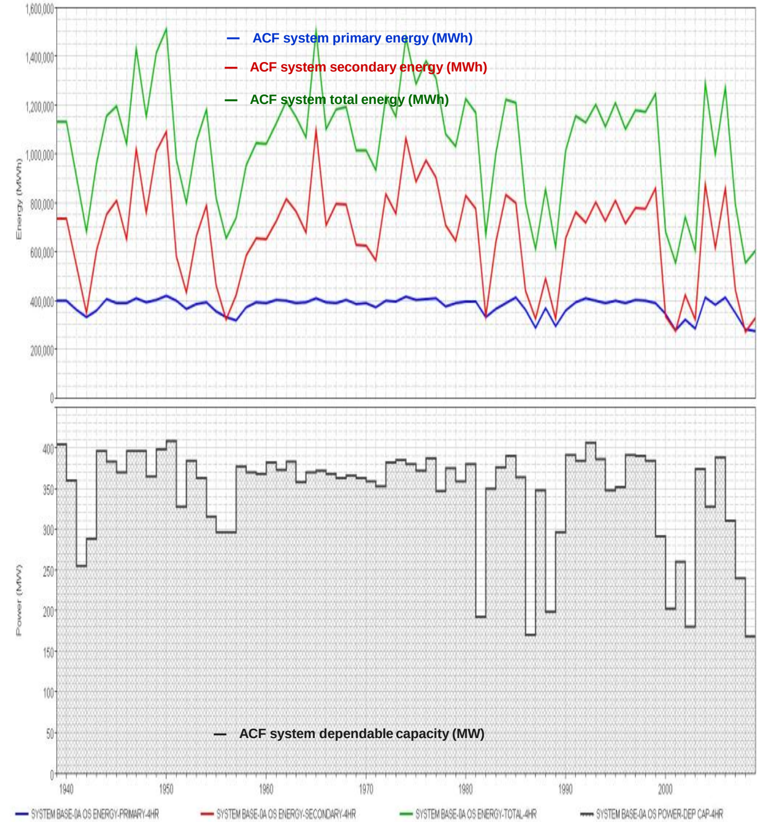
- Firm energy (FE), dependable capacity (DC) and non-firm energy (NFE) determined by rule-based operational models

- Firm energy – assured availability in the increment of load to be carried

- Non-firm energy – all energy other than firm

- Dependable capacity, *DC = FE/HR,* HR = hours use of plant or system IC required in the load increment to be carried





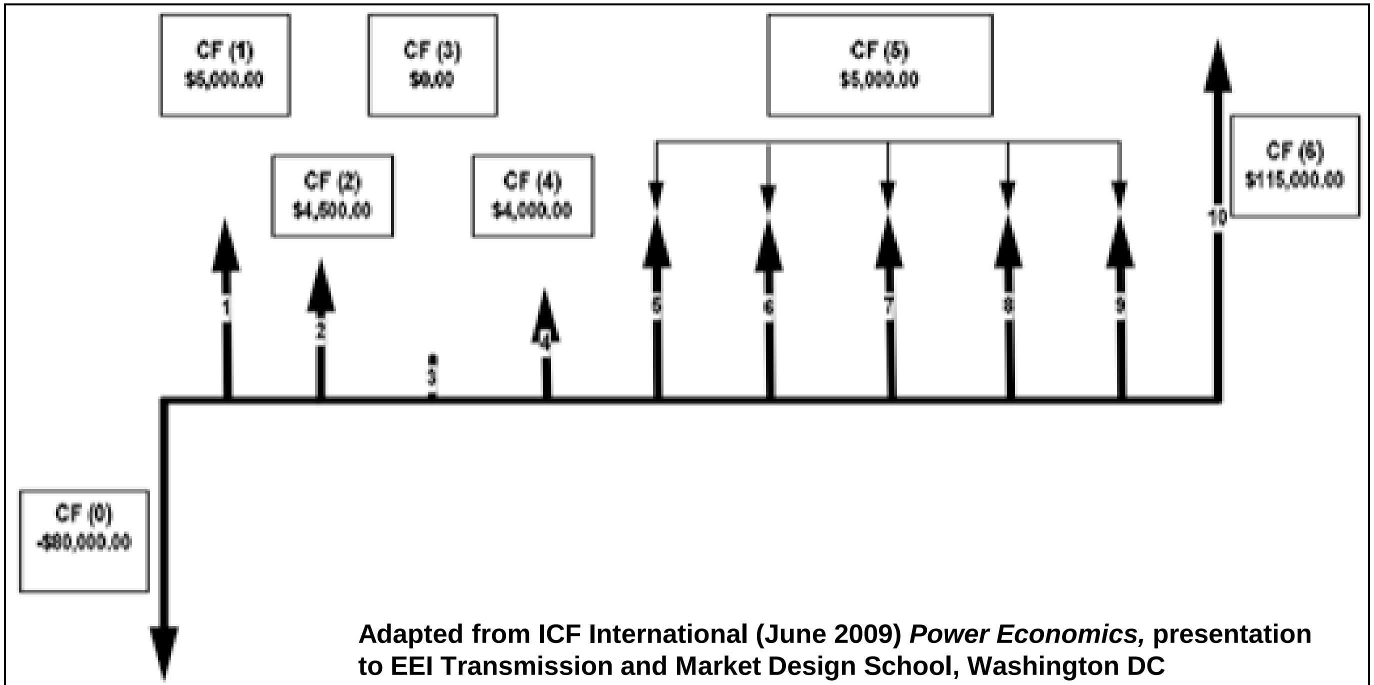
Feasibility analysis – federal hydropower

Federal interest in water resource development is National Economic Development (NED) – increased net national output of goods and services

- **NED benefits** represent willingness-to-pay (WTP) for hydropower energy and capacity outputs, limited to replacement cost of the most likely private alternatives
  - Dependable capacity – avoided costs of private (thermal) capacity (steam, combustion turbine, combined cycle) displaced by hydro
  - Firm and non-firm energy – fuel and variable operating costs of thermal generation displaced by hydro
- **NED costs** reflect opportunity costs of resource use
  - Separable costs (costs to add power purpose to a multipurpose federal project, e.g. turbines, generators, switchgear), plus
  - Joint-use costs (costs of facilities serving all purposes, e.g. dam, spillway, outlet works)
- **Feasibility (NED plan)** determined by maximum net NED benefits
  - Construction of new project(s)
  - Reallocation/reoperation of existing project(s)

Feasibility analysis – private utilities

- **Economic feasibility** based on net revenue streams (income and expenditures) over project life cycle, comparing:
  - Net benefits or B/C ratio
  - Present worth
  - Average annual worth
  - Rate-of-return (ROR)
- **Expenditures** include initial and periodic capacity replacement costs, operations and maintenance, fuel costs, and licensing costs

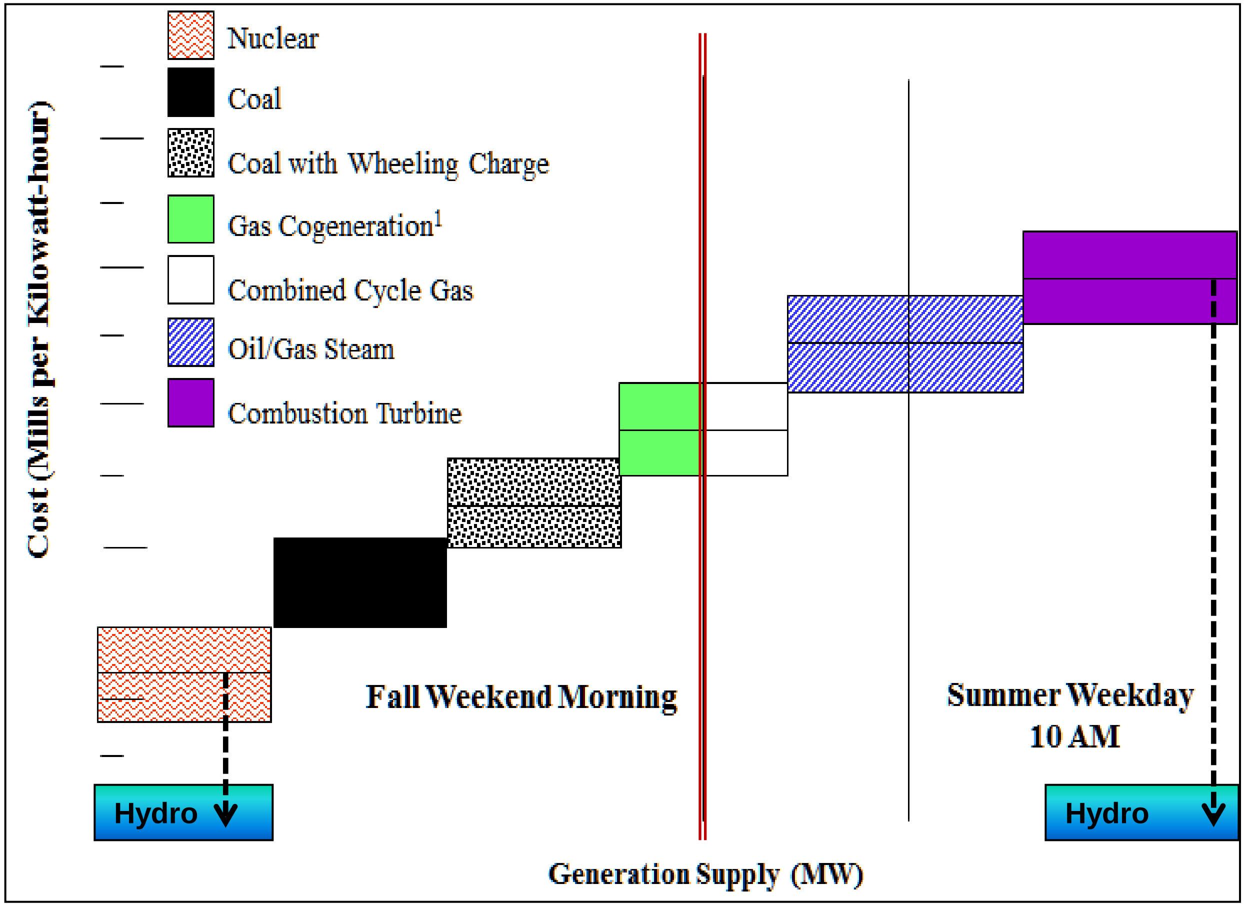


Adapted from ICF International (June 2009) *Power Economics,* presentation to EEI Transmission and Market Design School, Washington DC

Feasibility analysis – federal and private

Because hydropower is normally a small component of large thermal-based power systems with established rate structures, income/benefit is most commonly determined by production cost (system λ) savings achieved by substitution of hydro for thermal resources

Hourly system λ and competitive energy price



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Conclusions

- Hydropower is energy-limited but can be an important component of integrated electric power systems
  - Dependable capacity
  - Firm and non-firm energy
- Social, economic and environmental tradeoffs associated with hydro development can be simultaneously harmful and beneficial, e.g.:
  - Ecosystem alteration/destruction
  - Resettlement
  - Natural streamflow alteration
  - High development cost, low operating cost
  - Renewable energy
  - GHG emissions reduction
  - Consumptive water use reduction (vs. thermal)
  - Multipurpose reservoir development, economies of scope and scale

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Questions