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

Potential Energy

Kinetic Energy

Mechanical Energy

Electrical Energy

Electricity

Headwater

Forebay

Dam

Turbine

Generator

Afterbay
Hydropower in Context
Sources of Electric Power – US

- Coal 52%
- Natural Gas 16%
- Hydroelectric 7%
- Petroleum 3%
- Nuclear Electric 20%
- Other* 2%

* Other includes geothermal, biomass, wind, photovoltaic, and solar thermal. Includes utility and nonutility generation.
Renewable Energy Sources

Total others 0.9%
- Geothermal 0.6%
- Biomass 0.8%
- Wind 0.01%
- Photovoltaic 0.001%

Hydroelectric 99.1%

World Trends in Hydropower

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

<table>
<thead>
<tr>
<th>Producers</th>
<th>TWh</th>
<th>% of World total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>338</td>
<td>12.4</td>
</tr>
<tr>
<td>Brazil</td>
<td>306</td>
<td>11.2</td>
</tr>
<tr>
<td>United States</td>
<td>306</td>
<td>11.2</td>
</tr>
<tr>
<td>People’s Rep. of China</td>
<td>284</td>
<td>10.4</td>
</tr>
<tr>
<td>Russia</td>
<td>158</td>
<td>5.8</td>
</tr>
<tr>
<td>Norway</td>
<td>106</td>
<td>3.9</td>
</tr>
<tr>
<td>Japan</td>
<td>104</td>
<td>3.8</td>
</tr>
<tr>
<td>India</td>
<td>75</td>
<td>2.8</td>
</tr>
<tr>
<td>France</td>
<td>64</td>
<td>2.3</td>
</tr>
<tr>
<td>Venezuela</td>
<td>61</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Rest of the World</strong></td>
<td>924</td>
<td>34.0</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>2726</td>
<td>100.0</td>
</tr>
</tbody>
</table>

2003 data

* Excludes countries with no hydro production.

**Installed Capacity**

<table>
<thead>
<tr>
<th>Country</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>94</td>
</tr>
<tr>
<td>Canada</td>
<td>69</td>
</tr>
<tr>
<td>Brazil</td>
<td>65</td>
</tr>
<tr>
<td>People’s Rep. of China</td>
<td>58</td>
</tr>
<tr>
<td>Japan</td>
<td>46</td>
</tr>
<tr>
<td>Russia</td>
<td>44</td>
</tr>
<tr>
<td>Norway</td>
<td>28</td>
</tr>
<tr>
<td>India</td>
<td>27</td>
</tr>
<tr>
<td>France</td>
<td>25</td>
</tr>
<tr>
<td>Venezuela</td>
<td>13</td>
</tr>
</tbody>
</table>

**Country**

<table>
<thead>
<tr>
<th>Country</th>
<th>% of hydro in total domestic electricity generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>98.9</td>
</tr>
<tr>
<td>Brazil</td>
<td>83.8</td>
</tr>
<tr>
<td>Venezuela</td>
<td>66.0</td>
</tr>
<tr>
<td>Canada</td>
<td>57.5</td>
</tr>
<tr>
<td>Russia</td>
<td>17.2</td>
</tr>
<tr>
<td>People’s Rep. of China</td>
<td>14.9</td>
</tr>
<tr>
<td>India</td>
<td>11.9</td>
</tr>
<tr>
<td>France</td>
<td>11.4</td>
</tr>
<tr>
<td>Japan</td>
<td>9.9</td>
</tr>
<tr>
<td>United States</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Rest of the World</strong></td>
<td>15.2</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td>16.3</td>
</tr>
</tbody>
</table>

2002 data

Sources: United Nations, IEA.

2003 data
Major Hydropower Producers

![Bar chart showing major hydropower producers by country. Canada leads with the highest billion kilowatt-hours, followed by the United States, Brazil, China, Russia, Norway, Japan, India, Sweden, and France. Source: EIA, Annual Energy Review 1999, July 2000, Table 11.15.]
## World’s Largest Dams

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

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

Grand Coulee Dam (US) 7GW

Located in Washington
Uses of Dams – US

- Recreation: 35%
- Stock/farm pond: 18%
- Flood control: 15%
- Hydroelectricity: 2%
- Public water supply: 12%
- Irrigation: 11%
- Other: 7%

Source: U.S. Army Corps of Engineers, National Inventory of Dams
History of Hydro Power
Early Irrigation Waterwheel

A noria (Arabic: ناعورة, nāʿūra)

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.

The norias of Hama on the Orontes River in Syria

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.

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

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.
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**
  - \( \text{head} \times \text{flow} \)

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.
Types of Hydroelectric Installation

Figure 5.13 Types of hydroelectric installation

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

Transmission lines - conduct electricity, ultimately to homes and businesses

Dam - stores water

Penstock - Carries water to the turbines

Generators - rotated by the turbines to generate electricity

Turbines - turned by the force of the water on their blades

Cross section of conventional hydropower facility that uses an 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
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

Power spectrum of a pump storage power plant

Output in Megawatt

Time of Day

0 6 12 18 24

-500 0 500 1000

Pump power
Top power
Turbine Design

Francis Turbine
Kaplan Turbine
Pelton Turbine
Turgo Turbine
New Designs
Types of Hydropower Turbines

Figure 5.15 Types of turbine runner
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
Horizontal Kaplan Turbine

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
Turgo Turbine

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

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

($H = \text{head in meters}$)

Turbine Ranges of Application

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

## Head Pressure

<table>
<thead>
<tr>
<th>Impulse</th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelton Turgo</td>
<td>Pelton Turgo</td>
<td>Crossflow Turgo</td>
<td>Crossflow</td>
</tr>
<tr>
<td>Multi-jet Pelton</td>
<td>Multi-jet Pelton</td>
<td>Multi-jet Pelton</td>
<td></td>
</tr>
<tr>
<td>Reaction</td>
<td>Francis Pump-as-Turbine</td>
<td>Propeller Kaplan</td>
<td></td>
</tr>
</tbody>
</table>

*Boyle, Renewable Energy, 2nd edition, Oxford University Press, 2003*
Fish Friendly Turbine Design
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%

Hydropower Calculations

\[ P = g \times \eta \times Q \times H \]

\[ P \approx 10 \times \eta \times Q \times H \]

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

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 ($\eta$) of 83%.

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

- $P \approx 10\eta Q H = 10(0.83)(0.01)(25) = 2.075$ \hspace{1cm} \approx 2.1 \, \text{kW}$

Example 1b

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

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

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
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.

- \( P \approx 10 \eta QH = 10(0.83)(6000)(100) \)
  \( \approx 4.98 \) million kW = 4.98 GW (gigawatts)

- \( E = P \times t = 4.98\text{GW} \times 24 \text{ hrs/day} \times 365 \text{ days/yr} \)
  \( = 43,625 \text{ GWh} = 43.6 \text{ TWh (terawatt hours)} \)

- People = \( E \div 3000 = 43.6 \text{ TWh} / 3,000 \text{ kWh} \)
  \( = 1.45 \text{ million people} \)

- (This assumes maximum power production 24x7)

Economics of Hydropower
Production Expense Comparison

![Average Power Production Expense per KWh](chart)

- **Fossil-Fueled Steam**
- **Nuclear**
- **Hydroelectric**
- **Gas Turbine**

- **Cents per Kilowatthour**
- **Fuel**
- **Maintenance**
- **Operation**
Capital Costs of Several Hydro Plants

<table>
<thead>
<tr>
<th>plant</th>
<th>date</th>
<th>planned capacity</th>
<th>capital cost per kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itaipú</td>
<td>1984–91</td>
<td>12.6 GW</td>
<td>$1600</td>
</tr>
<tr>
<td>Gabcikovo-Nagymaros¹</td>
<td>1977–</td>
<td>0.88 GW</td>
<td>$1200</td>
</tr>
<tr>
<td>Three Gorges²</td>
<td>1993–</td>
<td>18.2 GW</td>
<td>$1200</td>
</tr>
</tbody>
</table>

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

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 \( \sim $20 \) million
  - Negligible ongoing costs
  - Ancillary benefits from dam
    - flood control, recreation, irrigation, etc.

- **50 MW combined-cycle gas turbine**
  - \( \sim $20 \) million purchase cost of equipment
  - Significant ongoing fuel costs

- Short-term pressures may favor fossil fuel energy production

Environmental Impacts
Impacts of Hydroelectric Dams

- Energy Options
- Water Supply
- Sedimentation
- Recreation
- Flooded habitats, culture and homes
- Greenhouse Gas Emissions (from flooded vegetation)
- Maintenance or Decommissioning
- Displaced People Protest
- Hydropower for electricity
- Environmental Flow Requirements
- Licencing Issues
- Loss of Downstream Aquifers
- River Bank Erosion
- Trans-boundary water competition
- Loss of livelihood from fisheries
- Salinity, Waterlogging
- Food from irrigation
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

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions-free, with virtually no CO2, NOX, SOX, hydrocarbons, or particulates</td>
<td>Frequently involves impoundment of large amounts of water with loss of habitat due to land inundation</td>
</tr>
<tr>
<td>Renewable resource with high conversion efficiency to electricity (80+%)</td>
<td>Variable output – dependent on rainfall and snowfall</td>
</tr>
<tr>
<td>Dispatchable with storage capacity</td>
<td>Impacts on river flows and aquatic ecology, including fish migration and oxygen depletion</td>
</tr>
<tr>
<td>Usable for base load, peaking and pumped storage applications</td>
<td>Social impacts of displacing indigenous people</td>
</tr>
<tr>
<td>Scalable from 10 KW to 20,000 MW</td>
<td>Health impacts in developing countries</td>
</tr>
<tr>
<td>Low operating and maintenance costs</td>
<td>High initial capital costs</td>
</tr>
<tr>
<td>Long lifetimes</td>
<td>Long lead time in construction of large projects</td>
</tr>
</tbody>
</table>
# Three Gorges – Pros and Cons

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

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

Source: ChinaOnLine, 2000

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
Regional Hydropower Potential

Table 5.3 Regional hydro potential and output

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

* Based on average output for the four years 1999–2002
Source: Adapted from WEC, 2003b and BP, 2003
Opportunities for US Hydropower

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

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

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>atto</td>
<td>a</td>
<td>$10^{-18}$</td>
<td>kilo</td>
<td>k</td>
<td>$10^3$</td>
</tr>
<tr>
<td>femto</td>
<td>f</td>
<td>$10^{-15}$</td>
<td>mega</td>
<td>M</td>
<td>$10^6$</td>
</tr>
<tr>
<td>pico</td>
<td>p</td>
<td>$10^{-12}$</td>
<td>giga</td>
<td>G</td>
<td>$10^9$</td>
</tr>
<tr>
<td>nano</td>
<td>n</td>
<td>$10^{-9}$</td>
<td>tera</td>
<td>T</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>micro</td>
<td>μ</td>
<td>$10^{-6}$</td>
<td>peta</td>
<td>P</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>milli</td>
<td>m</td>
<td>$10^{-3}$</td>
<td>exa</td>
<td>E</td>
<td>$10^{18}$</td>
</tr>
</tbody>
</table>

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
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
Evolution of Hydro Production

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

Francis Turbine Cross-Section
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)