SUSTAINABLE ENERGY

Prof. Michael W. Golay
Nuclear Engineering Dept.
HYDROPOWER
• Some facts and figures
• Large-scale versus small scale
• High head versus low–head
• Energy conversion technology
• Environmental and social impacts
• Economic issues
FOUR TYPES OF HYDROPOWER SYSTEMS

1. Impoundment Involving Dams: e.g., Hoover Dam, Grand Coulee

2. Diversion or Run-of-River Systems: e.g., Niagara Falls

3. Pumped Storage
   - Two way flow
   - Pumped up to a storage reservoir and returned to lower elevation for power generation

4. Tidal: e.g., la Rance
BOSTON BACK BAY

Photo by Peter Stevens on Flickr.
BC BEAVER DAM
• 97% renewable energy
• 57 hydroelectric generating stations (35,647 MW)
• 26 reservoirs (capacity of 175 TWh/year)
• 1 nuclear power plant
• Annual investment: $2 billion
Caniapiscau Reservoir is a man-made lake, created as part of the La Grande Complex (James Bay) Hydro-electric Project.

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

Aerial photo of Caniapiscau Reservoir removed due to copyright restrictions.
THREE GORGES DAM

BONNEVILLE DAM
ITAIPU DAM

Photo by Herr stahlhoefer on Wikimedia Commons.
ITAIPU DAM
ASWAN DAM

Photos by Image Science & Analysis Laboratory, NASA Johnson Space Center and NASA Visible Earth, Goddard Space Flight Center.
COMMON FEATURES OF CONVENTIONAL HYDROPOWER INSTALLATIONS

Typical Hydroelectric Dam

- **Generators**: Rotated by the turbines to generate electricity
- **Transmission lines**: Conduct electricity, ultimately to homes and businesses
- **Dam**: Stores water
- **Penstock**: Carries water to the turbines
- **Cross section of conventional hydropower facility that uses an impoundment dam**: Turbines - Turned by the force of the water on their blades

Image by MIT OpenCourseWare. Adapted from Tennessee Valley Authority.
The characteristic components of a river-diversion hydroelectric plant.
HYDRO POWER – SOME FACTS AND FIGURES

• Current World Hydropower Production (2006)
  - ~ 3000 TWh -- about 20% of the world’s electricity and about 88% of electricity from renewable sources
  - ~ 777 GWe of capacity in 150 countries

• US capacity 100,451 MWe (2009)
  - 78,951 MWe conventional hydro
  - 21,500 MWe pumped storage
  - About 8% of US electricity equivalent to 2.9 quads
  - Approximately 70% of US renewable energy

• Average Capacity/Availability Factor – 42% (~6% of total capacity)
COMPARISON OF ELECTRIC GENERATION CAPACITY IN NORTH AMERICA (2006)

**United States**
- Installed capacity: 1,076,000 MW
- Electricity generation: 4,064 TWh

**Canada**
- Installed capacity: 124,000 MW
- Electricity generation: 592 TWh

**Québec**
- Installed capacity: 40,000 MW
- Electricity generation: 180 TWh

Image by MIT OpenCourseWare. Source: Statistics Canada.
TRANSMISSION SYSTEM

<table>
<thead>
<tr>
<th>Neighboring system</th>
<th>Import mode (MW)</th>
<th>Export mode (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>1,100</td>
<td>2,000</td>
</tr>
<tr>
<td>Ontario</td>
<td>1,945</td>
<td>2,705</td>
</tr>
<tr>
<td>New England</td>
<td>2,070</td>
<td>2,275</td>
</tr>
<tr>
<td>New-Brunswick</td>
<td>785</td>
<td>1,080</td>
</tr>
<tr>
<td>Newfoundland and Labrador</td>
<td>5,150</td>
<td>0</td>
</tr>
</tbody>
</table>

Courtesy of Hydro-Québec. Used with permission.
Map of projected Hydro-Quebec hydroelectric construction removed due to copyright restrictions. Please see this map of current Hydro-Quebec construction instead.
HYDRO POWER – SOME FACTS AND FIGURES, continued

• Big Range in Capacity and Size
  ■ Power capacity – 1 kWe to 14500 MWe
  ■ Hydraulic head < 1 m to 1500 m (from low-head to high-head) (S. Fiorano, Italy)
  ■ Largest earth dam height – 300 m (Tajikistan)
  ■ Largest reinforced concrete dam height – 305 m (China)
  ■ Reservoir volume – 180 km$^3$ (Zimbabwe)
  ■ Reservoir area – 8,482 km$^2$ (Lake Volta, Ghana)

• Theoretical Potential, Technically Exploitable –
  ■ 15000 TWh/yr or about 4,000,000 MWe of capacity
### REPRESENTATIVE MEGA-SCALE HYDROPOWER PROJECTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Type</th>
<th>Capacity, MWe</th>
<th>Reservoir size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Coulee</td>
<td>Columbia River, Lake Roosevelt, Washington</td>
<td>Impoundment dam, 550 ft (170m) high</td>
<td>6809</td>
<td>9.6 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.9 km³</td>
</tr>
<tr>
<td>Niagara Falls</td>
<td>Niagara River, New York</td>
<td>Diversion, run of river</td>
<td>2400</td>
<td>nil</td>
</tr>
<tr>
<td>Hoover Dam</td>
<td>Colorado River, Lake Mead, Nevada</td>
<td>Impoundment dam, 726 ft (223m) high</td>
<td>2080</td>
<td>28.5 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35.2 km³</td>
</tr>
<tr>
<td>Norris Dam TVA</td>
<td>Clinch River, Norris Lake, Tennessee</td>
<td>Impoundment dam, 265 ft (81m) high</td>
<td>131.4</td>
<td></td>
</tr>
<tr>
<td>Glen Canyon</td>
<td>Colorado River, Lake Powell, Arizona</td>
<td>Impoundment dam, 710 ft (261m) high</td>
<td>1296</td>
<td>24.3 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 km³</td>
</tr>
<tr>
<td>James Bay Project</td>
<td>La Grande 1, 2A, 3, 4 Robert-Bourassa Lafarge 1, 2</td>
<td>Impoundment and run-of-river, multiple dams</td>
<td>8671</td>
<td>&gt;100 Quabbins!!</td>
</tr>
<tr>
<td></td>
<td>Brisy Eastmain 1, 1A</td>
<td></td>
<td>+5616</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+1197</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+469</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+768</td>
<td></td>
</tr>
<tr>
<td>Itaipu</td>
<td>Parana River, Itaipu Lake, Paraguay/Brazil</td>
<td>Impoundment dam, 643 ft (196 m) high</td>
<td>14,000</td>
<td>23.5 x 10^{12} acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29 million km³</td>
</tr>
<tr>
<td>Three Gorges</td>
<td>Yangze River, Three Gorges Lake China</td>
<td>Impoundment dam, 607 ft (185 m) high</td>
<td>18,200</td>
<td>31.8 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39.3 km³</td>
</tr>
<tr>
<td>Guri</td>
<td>Caroni River, Venezuela</td>
<td>Impoundment dam, 531 ft (162 m) high</td>
<td>10,235</td>
<td>109.4 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>135 km³</td>
</tr>
<tr>
<td>Krasnoyarsk</td>
<td>Yenisey River, Krasnoyarsk Lake, Russia</td>
<td>Impoundment dam, 407 ft (124 m) high</td>
<td>6,000</td>
<td>59.4 million acre ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>73.3 km³</td>
</tr>
</tbody>
</table>

HYDROPOWER IS STRATEGICALLY IMPORTANT WORLDWIDE (2008)

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

1,560 North American Plants (5,000 Units)
13,000 International Plants (42,000 Units)
World Total = 3,100,139 GWh/yr
World Total = $50,000,000,000/yr
# TEN OF THE LARGEST HYDROELECTRIC PRODUCERS (2009)

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual hydroelectric production (TWh)</th>
<th>Installed capacity (GW)</th>
<th>Capacity factor</th>
<th>% of total capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>585.2</td>
<td>196.79</td>
<td>0.37</td>
<td>22.25</td>
</tr>
<tr>
<td>Canada</td>
<td>369.5</td>
<td>88.974</td>
<td>0.59</td>
<td>61.12</td>
</tr>
<tr>
<td>Brazil</td>
<td>363.8</td>
<td>69.080</td>
<td>0.56</td>
<td>85.56</td>
</tr>
<tr>
<td>United States</td>
<td>250.6</td>
<td>79.511</td>
<td>0.42</td>
<td>5.74</td>
</tr>
<tr>
<td>Russia</td>
<td>167.0</td>
<td>45.000</td>
<td>0.42</td>
<td>17.64</td>
</tr>
<tr>
<td>Norway</td>
<td>140.5</td>
<td>27.528</td>
<td>0.49</td>
<td>98.25</td>
</tr>
<tr>
<td>India</td>
<td>115.6</td>
<td>33.600</td>
<td>0.43</td>
<td>15.80</td>
</tr>
<tr>
<td>Venezuela</td>
<td>86.8</td>
<td>16.209</td>
<td>0.46</td>
<td>44.34</td>
</tr>
<tr>
<td>Japan</td>
<td>69.2</td>
<td>27.229</td>
<td>0.37</td>
<td>7.21</td>
</tr>
</tbody>
</table>
## FUTURE HYDROELECTRIC PROJECTS OVER 5,000 MW

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (MW)</th>
<th>Country</th>
<th>Construction</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Sea Dam</td>
<td>50,000</td>
<td>Djibouti</td>
<td>Proposed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yemen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grand Inga Dam</td>
<td>39,000</td>
<td>Congo DR</td>
<td>2014</td>
<td>2025</td>
</tr>
<tr>
<td>Three Gorges Dam</td>
<td>22,500</td>
<td>China</td>
<td>1994</td>
<td>2011</td>
</tr>
<tr>
<td>Baihetan Dam</td>
<td>13,050</td>
<td>China</td>
<td>2009</td>
<td>2015</td>
</tr>
<tr>
<td>Belo Monte Dam</td>
<td>11,233</td>
<td>Brazil</td>
<td>Proposed</td>
<td></td>
</tr>
<tr>
<td>Wudongde Dam</td>
<td>7,500</td>
<td>China</td>
<td>2009</td>
<td>2015</td>
</tr>
<tr>
<td>Country</td>
<td>Hydro as % of total electricity</td>
<td>Ratio of theoretical potential to actual</td>
<td>Ratio of economic potential to actual</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Norway</td>
<td>100</td>
<td>5.77</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>91.7</td>
<td>5.4</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>80</td>
<td>–</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>63</td>
<td>3.81</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>25</td>
<td>4.2</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>20</td>
<td>1.15</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>17</td>
<td>10.1</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>14</td>
<td>31.3</td>
<td>3.13</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>10</td>
<td>1.82</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>19</strong></td>
<td><strong>18.34</strong></td>
<td><strong>&gt;2.78</strong></td>
<td></td>
</tr>
</tbody>
</table>

## HYDROPOWER CAPACITY ESTIMATES

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

Source: World Energy Council
Total power from hydropower including both static (PE) and dynamic (KE) contribution

\[
Power = (\text{total hydraulic head}) \times (\text{volumetric flow rate}) \times (\text{efficiency})
\]

\[
Power = (\rho gZ + \frac{1}{2} \rho \Delta v^2) \times Q \times \varepsilon
\]

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

\[
Power = 9.81 \times 10^3 Z Q \varepsilon \text{ in watts} = 9.81 \times 10^{-3} Z Q \varepsilon \text{ in MWe}
\]
TURBINE TYPES

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

Images of turbines removed due to copyright restrictions. Please see "Types of Hydropower Turbines."

http://www1.eere.energy.gov/water/hydro_turbine_types.html
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- Central and South America
  665,316 GWh/yr
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1,560 North American Plants (5,000 Units)
13,000 International Plants (42,000 Units)
World Total = 3,100,139 GWh/yr
World Total = $50,000,000,000/yr
HYDRAULIC TURBINES: DOMAINS OF HEAD AND SCALE IN THE ENGINEERING PRACTICE OF PELTON, FRANCIS AND KAPLAN TURBINES

Image by MIT OpenCourseWare.
**MAJOR ATTRIBUTES OF HYDROPOWER**

<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 capability</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 kWe to 10,000 MWe</td>
<td>Health impact in developing countries</td>
</tr>
<tr>
<td>Low operating and maintenance cost</td>
<td>High initial capital costs</td>
</tr>
<tr>
<td>Long lifetime - 50 years typical</td>
<td>Long lead time in construction in mega-sized projects</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
HYDRO POWER – ECONOMIC ISSUES

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

- Land Use – Inundation and Displacement of People
- Impacts on Natural Hydrology
  - Infiltration
  - Increase evaporative losses
  - Altering river flows and natural flooding cycles
  - Sedimentation/silting
- Water Chemistry Changes
  - Mercury, nitrates, oxygen
  - Bacterial and viral infections (malaria, schistosomiasis, cholera,...)
**EFFECTS OF HYDROELECTRIC FACILITIES**

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

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

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

- http://www.worldenergy.org/
- http://hydropower.inel.gov/
- http://hydro.org/why-hydro/
- http://www.energy.ca.gov/hydroelectric/index.html
- http://www.unep.org/dams/WCD/
- http://www.ussdams.org
Introduction to Sustainable Energy
Fall 2010

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