Hydro Power – A Case Study

- Some facts and figures
- Large-scale versus small scale
- High head versus low–head
- Energy conversion technology
- Environmental and social impacts
- Economic issues

Resources on Hydropower Technology

In addition to Chapter 12 of the *Sustainable Energy* text

1. M. Brower, "Energy from Rivers and Oceans", Ch 6 in *Cool Energy*, p111-118, MIT Press, Cambridge, MA (1992)
2. *Hydropower Facts*, US Department of Energy (March, 1997)
3. Moreira and Poole, "Hydropower at its constraints," in *Renewable Energy*, eds. Johannson, Kelly, Reedy, and Williams Island Press, Washington (1993)
4. Boston Globe, "The Price of Power", article in The Boston Globe Magazine, (August 26, 1990)
5. X. Lei, "Going Against the Flow in China", *Science 280, p 24-26*

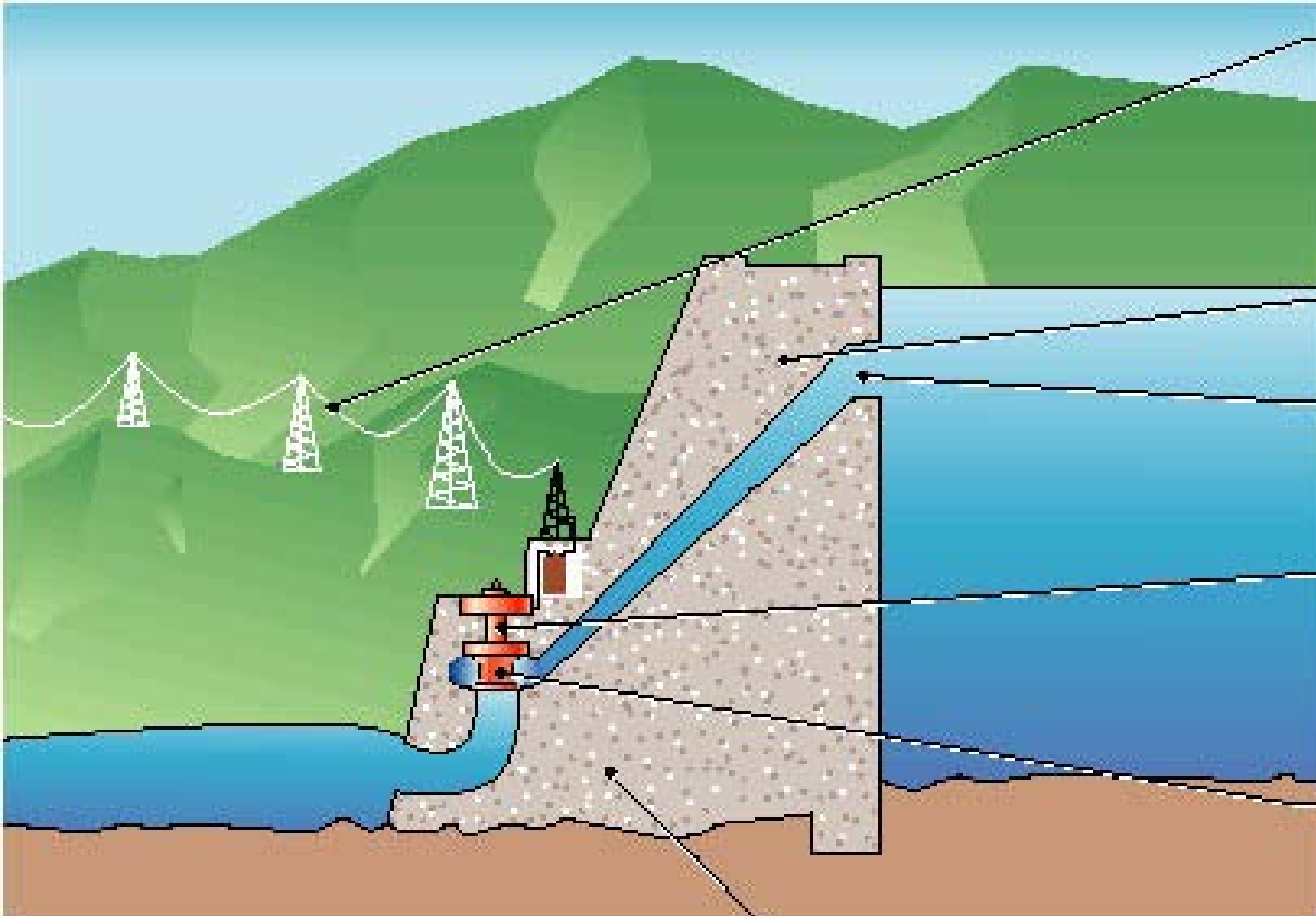
Archival web sites on hydropower

- *www.eren.doe.gov/RE/hydropower*
- *www.energy.ca.gov/electricity/hydro*
- *www.dams.org*
- *www.ussdams.org*

Three types of hydropower systems

1. **Impoundment involving dams**
   - eg. 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

Common features of conventional hydropower installations



Courtesy of Idaho National Laboratory.

Conventional high head run of river hydropower, e.g. Niagara Falls

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See Figure 12.2 in Tester, J. W., et al. *Sustainable Energy: Choosing Among Options*. Cambridge MA: MIT Press, 2005.

Hydro Power – Some Facts and Figures

- Current World Hydropower production
  ~ 2000 TWh/yr -- about 20% of the world's electricity
  ~ 635,000 MWe of capacity in 150 countries
- US capacity 103,800 MWe
  - 78,200 MWe conventional hydro
  - 25,600 MWe pumped storage
  - about 10% of US electricity equivalent to 3.1 quads
  - approximately 50% of US renewable energy
- Average capacity/availability factor – 42%

Hydro Power – Some Facts and Figures (continued)

- **Big range in capacity and size**
  - * power capacity – 1 kWe to 12000 MWe
  - * hydraulic head < 1 m to 1500 m (from low-head to high-head)
  - * largest earth dam height – 300 m (Tajikistan)
  - * largest reinforced concrete dam height– 285m (Switzerland)
  - * reservoir volume – $>10^6$ m^3 (Uganda)
  - * reservoir area – 9,600 km^2 (La Grande complex, Quebec)
  - * hydraulic head – 1 m to 1500 m (S. Fiorano, Italy)
- **Theoretical potential, technically exploitable** –
  15000 TWh/yr or about 4,000,000 MWe of capacity

Table 12.1 Representative Mega-scale Hydropower projects

Name	Location	Type	Capacity, MWe	Reservoir Size
Grand Coulee	Columbia River, Lake Roosevelt, Washington	Impoundment dam,550 ft (168m) high	6480	9.4 million acre ft
Niagara Falls	Niagara River New York	Diversion, run of river	1950	nil
Hoover Dam	Colorado River Lake Mead, Nevada	Impoundment dam, 726 ft (223m) high	1500	28.3 million acre ft 146,000 acres
Norris Dam TVA	Tennessee River Norris, Tennessee	Impoundment dam		
Glen Canyon	Colorado River, Lake Powell, Arizona	Impoundment dam, 710 ft (216 m) high	1500	27.0 million acre ft
La Grande complex +Churchill Falls + Nottaway-Broadback-Rupert	St James Bay Quebec and Labrador, Canada	Impoundment multiple dams,	10,000 +3200 +7000	> 100 Quabbins!!
Itaipa	Paraguay/Brazil	Impoundment dam, 150 m high	12,600	
Three Gorges	Yangze River China	Impoundment, dam	17,000	
Guri	Venezuela	Impoundment, dam	10,300	
Krasnoyarsk	Russia	Impoundment, dam	6,000	

Hydropower is strategically important worldwide

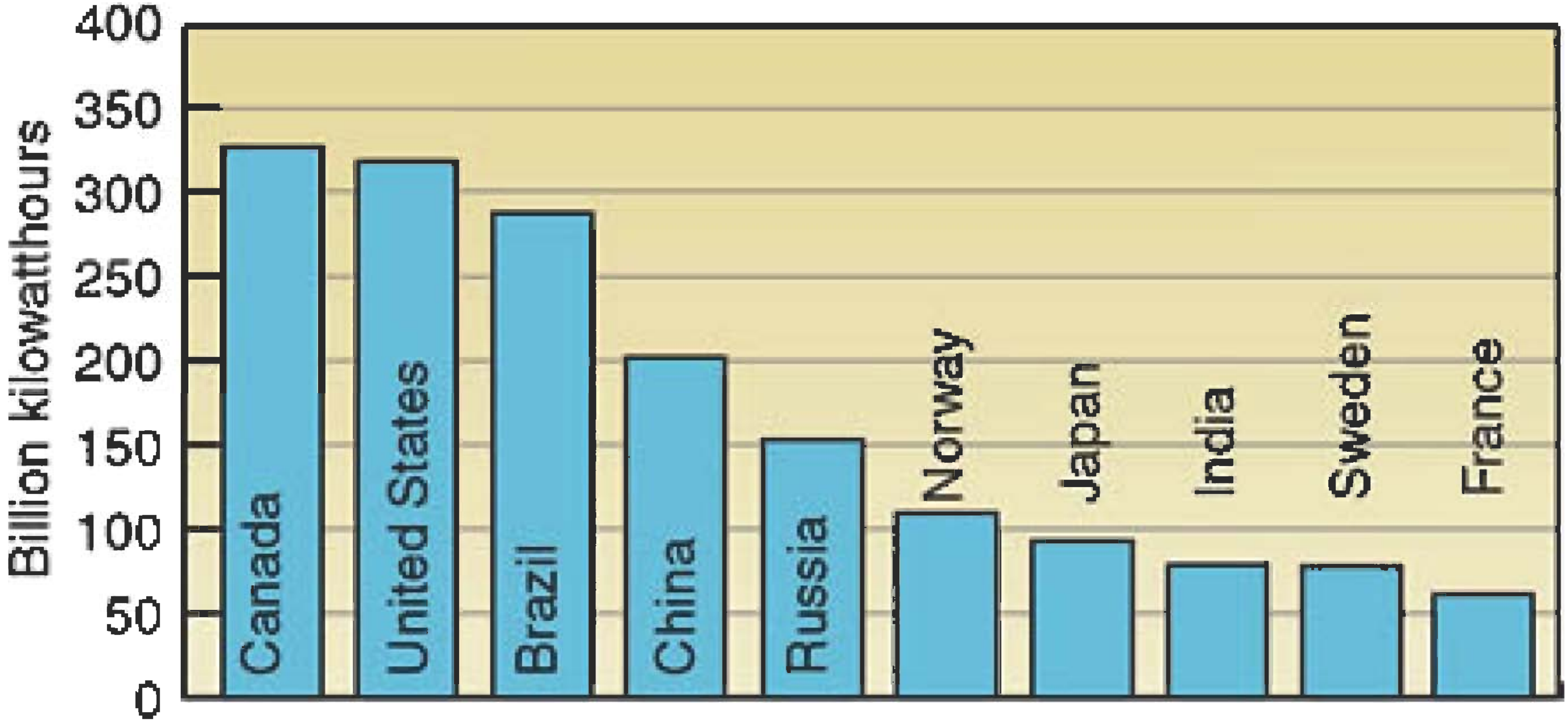
- North America
  569,000 GWh/yr
- South America
  388,000 GWh/yr
- Africa
  52,900 GWh/yr
- Europe
  284,000 GWh/yr
- Asia
  816,000 GWh/yr
- Australia
  39,000

1,560 North American Plants (5,000 Units)

13,000 International Plants (42,000 Units)

World Total = 2,150,000 GWh/Yr

World Total = $50,000,000,000/yr



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

Table 12.4 Potential for hydropower development in selected countries based on technical potential and economic potential in today's energy markets

Country	Hydro as % of total electricity	Ratio of Theoretical potential to actual	Ratio of Economic potential to actual
Norway	100	5.77	1.8
Brazil	91.7	5.4	3.0
Switzerland	80	-	1.1
Canada	63	3.81	1.54
India	25	4.2	3.0
France	20	1.15	1.0
China	17	10.1	6.6
Indonesia	14	31.3	3.13
United States	10	1.82	1.3
World total	**19**	**18.34**	**>2.78**

Sources: World Energy Conference, United Nations, MIT Energy Lab, Paul Scherrer Institute

Table 12.3 Hydropower capacity estimates by continent, based on large dam technology

Continent	Capacity in 2001 GWe	Capacity in 2001 TWh/yr	Maximum theoretical Potential TWh/yr	Technically possible TWh/yr	Economically possible TWh/yr
North America	154	743.2	6,150	2,700	> 1,500
South America	99	471.0	7,400	3,000	> 2,000
Africa	21	59.3	10,120	1,150	> 200
Europe	210	646.9	5,000	2,500	> 1,000
Asia	157	555.0	16,500	5,000	> 2,500
Oceania *	13	42.4	1,000	300	> 100
Total world	**654**	**2,518**	**46,170**	**14,650**	**> 7300**

Sources: World Energy Council (2001), WEC; International Commission on Large Dams, ICOLD (2001); World Commission on Dams (2001); Moreira and Poole (1993)

* includes Australia and New Zealand

Basic operating equations for hydropower

Total power from hydropower including both static (PE) and dynamic (KE) contribution

$$Power = (total\ \ hydrualic\ \ head) \times (volumetric\ \ flowrate) \times (efficiency)$$

$$Power\ \ = (\rho g Z + 1/2\,\rho \Delta(v^2\ )) \times Q \times \varepsilon$$

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

$$Power = 9.81 \times 10^3 ZQ\varepsilon\ \ in\,watts = \ 9.81 \times 10^{-3} ZQ\varepsilon\ \ \ in\,\mathrm{MWe}$$

Hydro Power – Energy Conversion Concepts

- High head (> 200 m) –Pelton impulse turbines
- Low head (6 to 300 m) Francis and Kaplan reaction turbines
- Ultra-low head (< 6 m) – Reaction turbines include air–driven, reversible Gorlov, Francis–type and run–of–river Schneider air–foil designs
- Typical efficiencies for PE + KE to electricity 80 to 85%
- Can be integrated into pumped energy storage systems
- Conversion technology for low–head similar to tidal power systems

Figure removed for copyright reasons. Schematics of Francis and Kaplan Turbines, from Franke et al. 1997.

Figure removed for copyright reasons.

See Figure 12.3 in Tester, J. W., et al. *Sustainable Energy: Choosing Among Options*. Cambridge MA: MIT Press, 2005.

Hydro Power – 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 (maleria, schitosomiasis, cholera,…)
- Seismic risks
- Structural dam failure risks

Table 12.5 Major attributes of hydropower

Positive	Negative
Emissions-free, with virtually no CO_2, NO_x, SO_x, 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 capability	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 kWe to 10,000 MWe	Health impacts in developing countries
Low operating and maintenance costs	High initial capital costs
Long lifetime – 50^+ years typical	Long lead time in construction of mega-sized projects

Global Water Resources

Surface water available 8600 km^3/a

2080 km^3/a not used | 2350 km^3/a utilized = 4430 km^3/a withdrawn

Domestic Use 5%

Agriculture 70%

Industry 25%

Number of countries (inhabitants) with water stress

2000	28	(335 million)
2025	50	(3,000 million)

Role of Groundwater

Water available
3000 km^3/a

Renewable use:
1000 km^3/a

Depletive use:
200 km^3/a

Despite smaller quantity special role due to long term storage and usually high quality

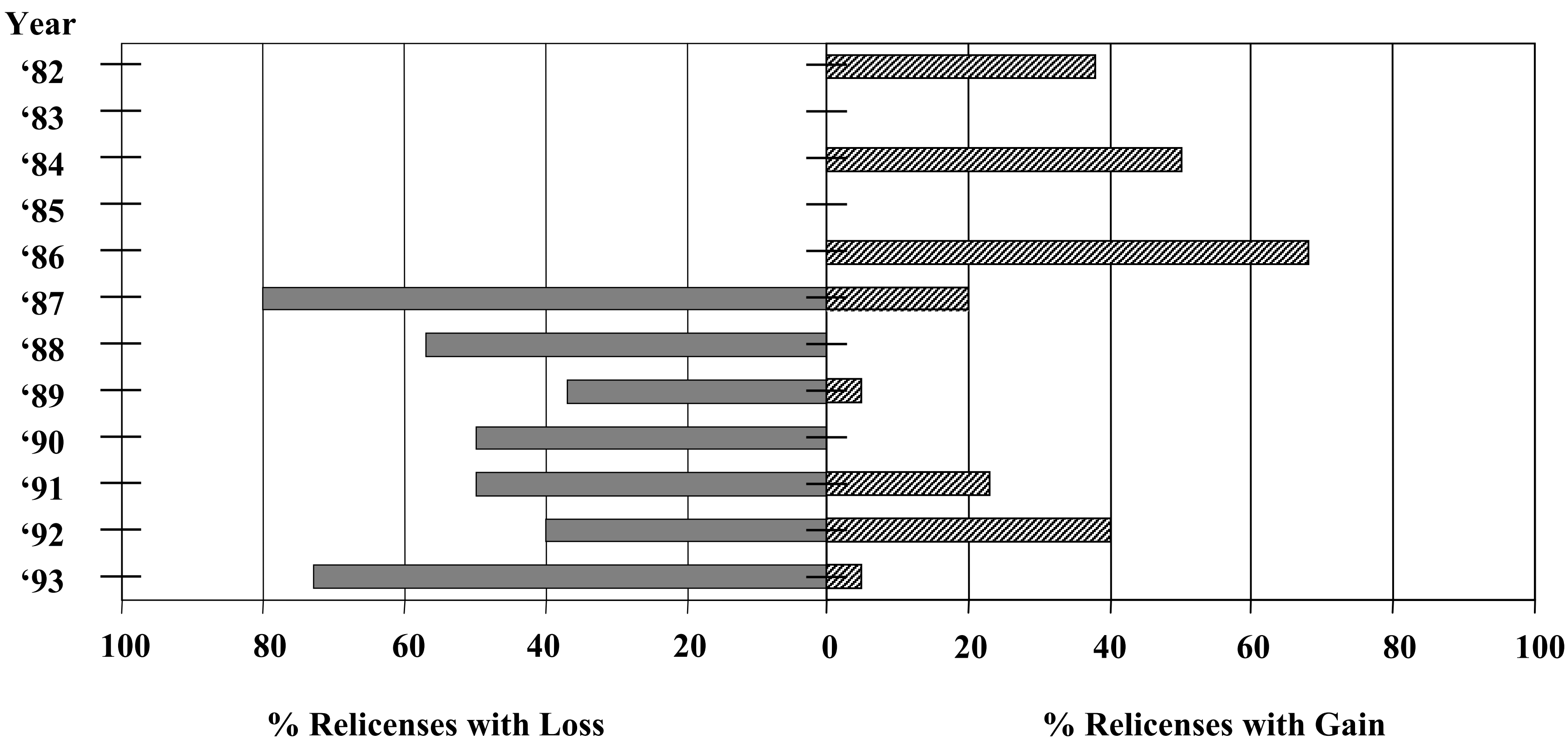
Hydro Power – Economic Issues

- 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

Hydropower is at Risk in the U.S.

- An average 8% production loss is due to relicensing and other regulatory pressures
- Real and perceived adverse environmental effects are hydropower’s major detriments
- Lost of hydropower capacity is being replaced by fossil-fuel-fired power plants (mostly gas at present)
- Almost non-existent Federal or Private R&D on Technology

Effects of Relicensing on Hydro Plant Output (1982-1993)



Short-Term Hydropower R&D Needs

- Fish passage requires robust technological solutions
- Quantification and integration of instream flow needs
- Variable speed turbines
- Optimization for multiple water uses
- Operational effects on reservoir ecology
- Improved numerical models of turbine system hydraulics

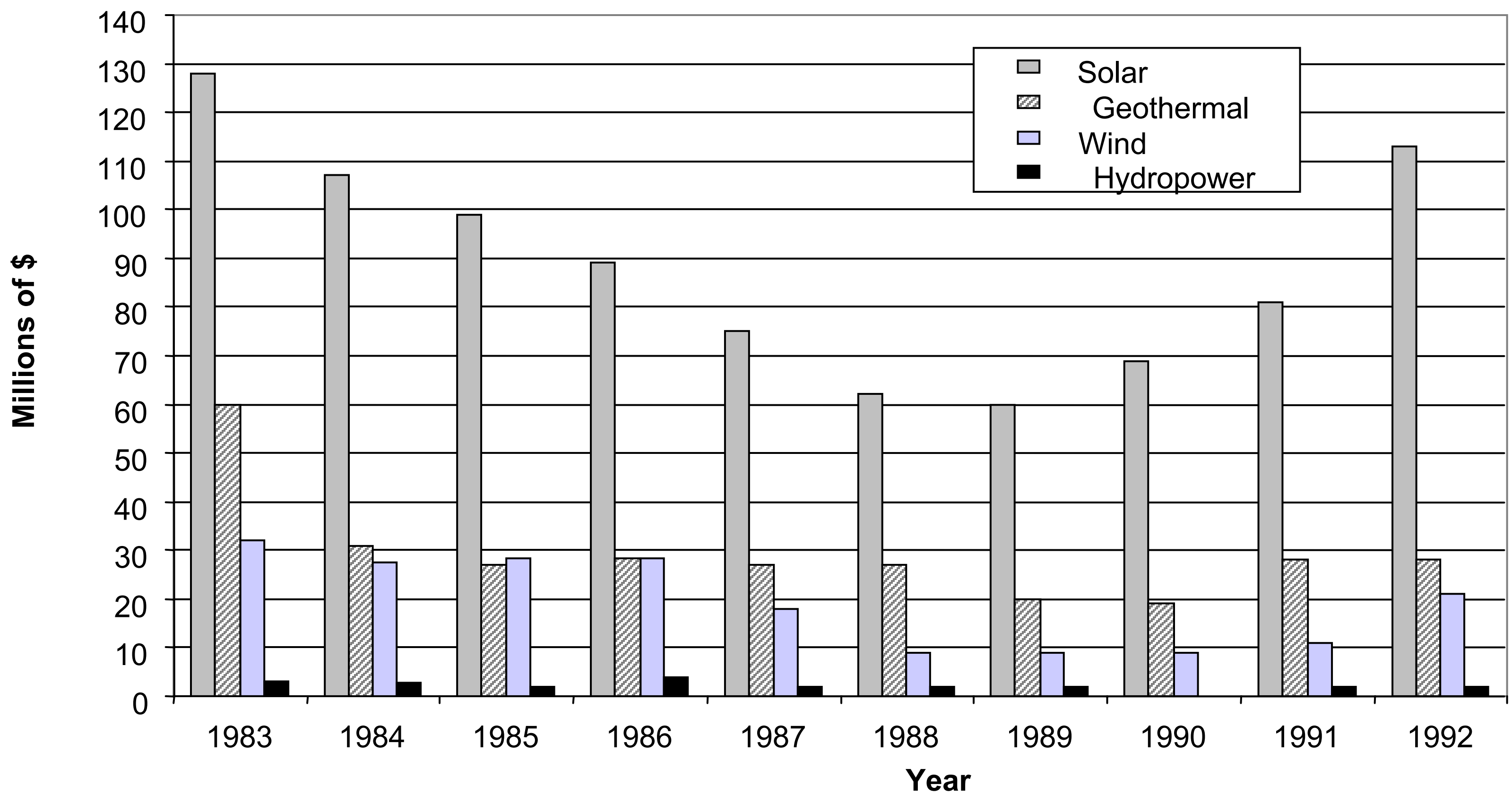


Figure 3. R&D Budget – Renewable Energy Sources, 1983 to 1992

Long Term Opportunity for Hydropower

- Capture the low-head, run-of-river hydro resource in a sustainable manner using new technology
  - Fish friendly turbines
  - Minimal water impoundment
  - Minimal impacts on aquatic ecology -- dissolved oxygen and other nutrients maintained at normal levels
  - No sediment buildup or depletion beyond normal levels

Fish Friendly high-head Hydroturbines

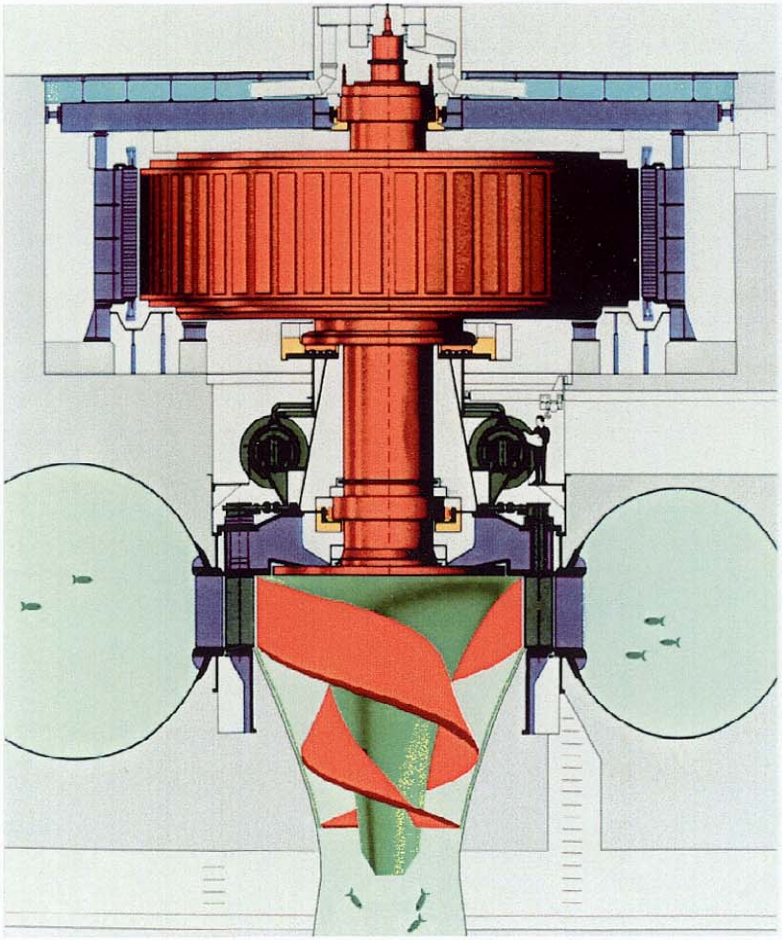


Figure 4. Schematic of the new ARL/NREC fish-friendly turbine. (Courtesy Alden Research Laboratory, Inc.)

Flow Assessment Using CFD

Once the overall dimensions were established and local refinements in the runner geometry were made to avoid severe turbulence and head loss-producing flow characteristics, VISIUN™ (a 3-D CFD program developed by NREC) was used to analyze the new runner, Case 3 design in Table 2 above. CFD programs solve the complicated Navier-Stokes equations governing fluids in motion by numerically integrating flow properties, such as velocity and pressure, over very small areas within a grid system throughout the flow field. Using an iterative procedure and starting with known hydraulic boundary conditions (e.g., head, velocity, and pressure at inlet and exit), the CFD program solves the equations over the entire grid system using an iterative procedure.

19

Alden Research Laboratory
Worcester, Mass

Low head hydropower systems have environmental advantages

Diagram removed for copyright reasons.

- Minimal land inundation
- Minimal change to hydrology
- Fish migration and passage
- Dispatchable power
- Small scale and modular

The End

Countries with the Largest Theoretical Hydroelectric Potential

	Theoretical Hydroelectric Potential (TWh/year)	Ratio of Economic Hydro Potential to Total 1980 Electricity Production	Ratio of Economic Hydro Potential to Actual 1980 Hydroelectricity Production
USSR	3942	0.9	6.1
Argentina	2432	4.9	13.1
China	1927	4.5	24.4
Zaire	1567	?	?
Brazil	1389	4.0	4.3
Colombia	1290	?	?
United States	1063	0.3	2.3
Burma	821	158	259
Canada	817	1.7	2.4
India	750	1.9	18
Indonesia	667	19	356
Vietnam	556	7.4	41
Norway	500	1.5	1.5
New Zealand	500	1.3	1.7
Venezuela	494	?	?
Turkey	436	3.2	6.6
Italy	341	0.3	1.0
Madagascar	320	271	949
Mexico	280	1.4	5.5
Peru	278	12	16
France	270	0.2	1.0
Equador	258	?	?
Ethiopia	228	82	117
Chile	224	7.7	12
Costa Rica	223	16	17
Bolivia	197	60	85
Popua-New Gui	197	112	361