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# **GRID-CONNECTED RENEWABLE ENERGY:**

## **HYDROELECTRIC POWER**

# Slide 1

## Grid-Connected Renewable Energy: Hydroelectric Power



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# PRESENTATION

- **Technology Overview**
- Global Status
- Hydro Economics
- Technical Issues & Solutions
- Best Practices

# Slide 2

## Presentation Contents

This module provides information on hydroelectric power generation and consists of the following sections:

**Section One** – The first section discusses hydropower concepts and technologies, and how to calculate power output.

**Section Two** – This section reports on the global status of hydroelectric power generation, and the impact of climate change.

**Section Three** – The third section discusses the economics of producing electricity from hydropower facilities.

**Section Four** – The fourth section addresses dam safety and other technical issues related to hydroelectric power, and how these issues can be resolved.

**Section Five** – The final section discusses best practices for enabling the development of hydroelectric projects.

This Hydroelectricity Module was authored by:

Carlos Yermoli  
President, Hydrosience Consulting  
cay@hydrosience-consulting.com

and

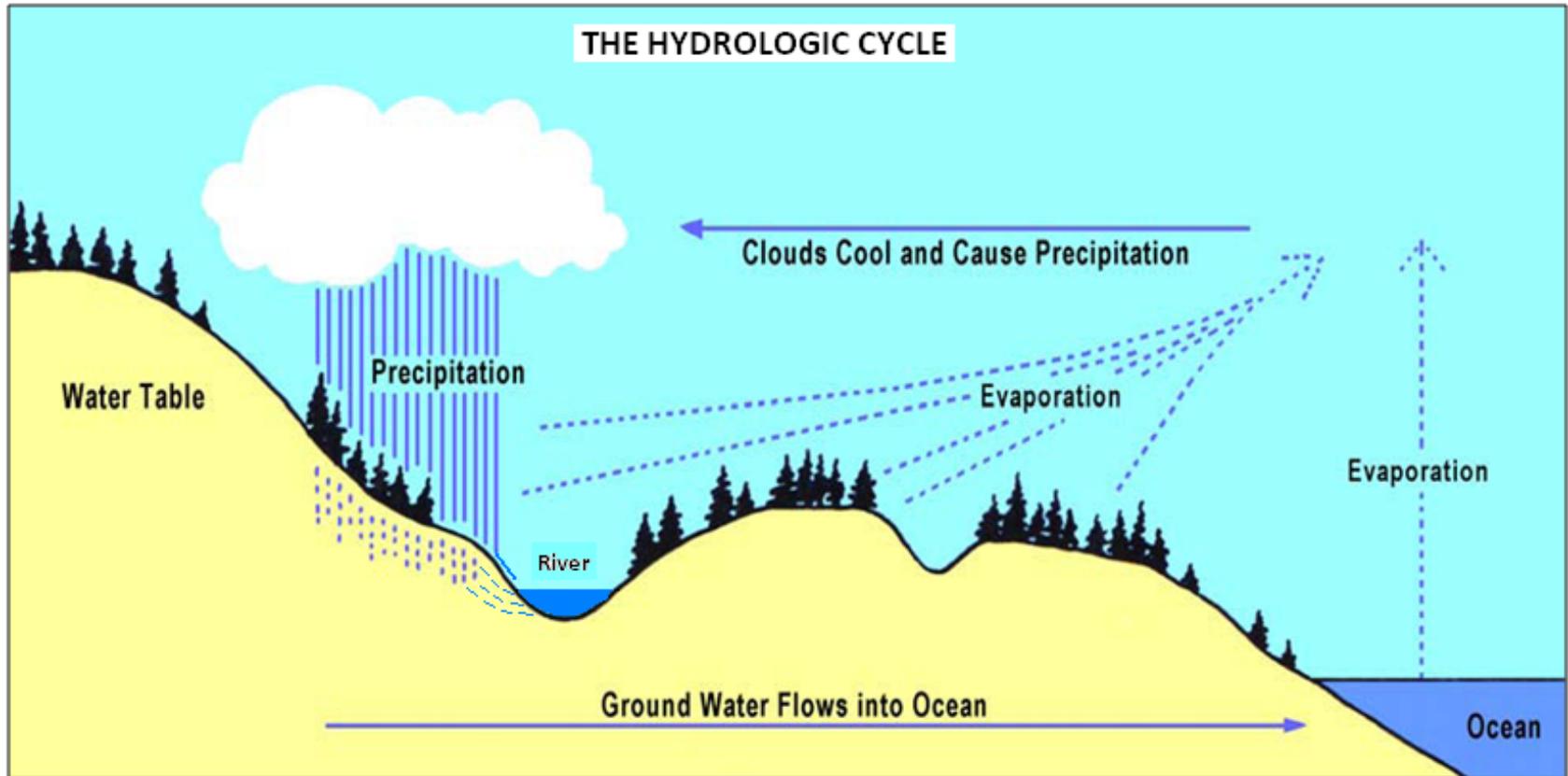
Krish Krishnan  
Office of Infrastructure and Engineering  
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# WATER AND ENERGY



# Slide 3

## Water and Energy

Naturally flowing water is a powerful source of renewable energy. The energy of the sun, acting over vast areas of the planet, evaporates water into clouds that move over mountains, where the water vapor condenses due to lower temperatures and precipitates in the form of rain or snow. Rain and snowmelt collect into creeks, which converge into rivers that flow to the sea, where the hydrologic cycle begins anew. A river can therefore be viewed as a highly concentrated form of energy waiting to be tapped.

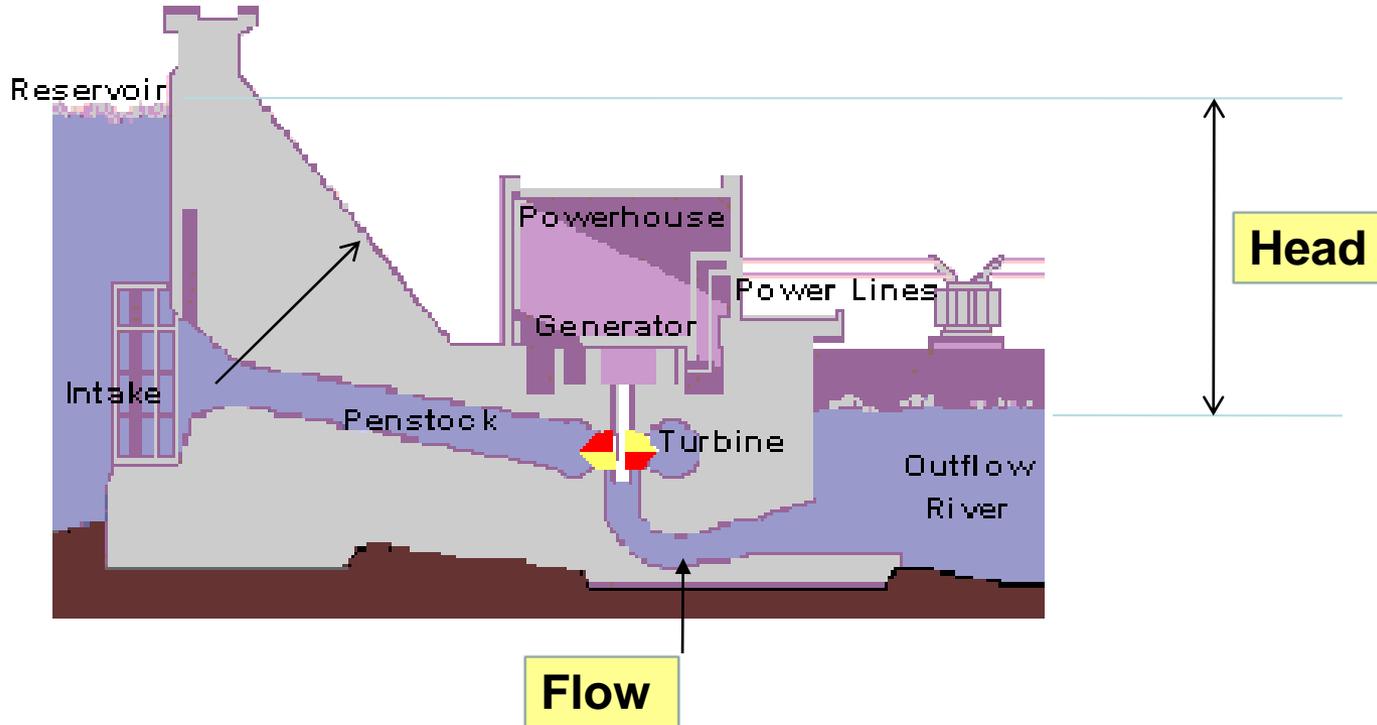
Hydropower is one of the most widely known forms of renewable energy. Early civilizations tapped the energy of moving water by using waterwheels to drive mills or mechanical pumps for irrigation. After the discovery of electric currents induced by moving magnets, waterwheels coupled to generators in 1880 emerged as the first technology used for large-scale electricity supply. Hydroelectric power (also known as “hydropower” or simply “hydro”) is one of the principal generation technologies today.

## References

- 334. How the Hydrologic Cycle Works



# HYDROPOWER CONCEPTS



$$\text{Power} = \text{Flow} \times \text{Head} \times \text{Efficiency}$$

# Slide 4

## Hydropower Concepts

Power from a hydroelectric plant depends on two key components: flow and head. Head refers to the difference in height between the source and the water's outflow. Flow refers to the speed and volume of water flowing through the site. Flow and head are of equal importance when determining power generation potential. For example, to double the power output, the options are either to double the head or double the flow. The choice depends on what is technically, financially, and environmentally feasible at a specific site. Developing head for generation may be achieved by constructing dams. Water flow can be increased by directing the water through channels, tunnels, or some combination thereof to increase water volume and speed.

It is easy to calculate a plant's hydroelectric power output.

### Example:

A plant has Head = 30 meters; Flow = 20 cubic meters per second; and efficiency = 0.85

The theoretical output is:

$$P = 9.81 \times (0.85 \times 20 \times 30) = 5,003 \text{ kilowatts (kW)} = 5 \text{ MW}$$

9.81 is the constant acceleration of gravity in  $\text{m/s}^2$ .

Actual output is reduced by the efficiencies of generating equipment and may vary considerably with changes in available flows and heads.

Because a river's flow is the "fuel" for hydro generation, without any storage, power output from a plant may be zero when the available flow is less than the amount needed to operate a turbine. With daily, seasonal, or over-the-year storage, actual generation from a hydro plant can be almost independent of actual river flow and the plant can generate at full capacity as long as water is available. This capability to "store energy" as water and quickly release it to meet sudden changes in electricity demand is a key advantage hydro power and makes it desirable to system operators.

### Other Useful Concepts

- **Installed Capacity (IC)** = the maximum power output  $P$  for which the generators are designed
- **Mean Annual Energy (MAE)** = the average annual energy production taking into account all hydrologic conditions
- **Mean Power Output (MP)** =  $\text{MAE} / 8,760$  = the average power output expected during the life of the plant
- **Capacity Factor (CF)** =  $\text{MP} / \text{IC}$  = the ratio between mean power output and installed capacity

### Example:

A plant has an IC = 10 MW and MAE = 35,000 MWH

$$MP = 35,000 / 8,760 = 4 \text{ MW}$$

$$CF = MP/IC = 4/10 = 0.40$$

Note:

Capacity factor is a good indicator of likely financial performance because MP determines project benefits and IC strongly impacts project costs. Generally speaking, a high CF is a good sign.

However, the production and revenue from different types of hydro facilities can vary greatly depending upon other factors besides flow, head, and efficiency. While it is true that low head and high head hydro facilities can operate similarly, in some jurisdictions high head, low flow plants are used primarily for regulation, while low head, high flow plants are used more to supply baseload power. The MAE, MP, and CF curves of a plant relying mostly on snowmelt will be very different from those of a plant relying on rain only, since the former has huge production during the spring runoff, and likely less production the rest of the year. Projects that incorporate objectives beyond power generation, such as supplying irrigation water, will have different MAEs and capacity factors than those installed purely for power production.

## References

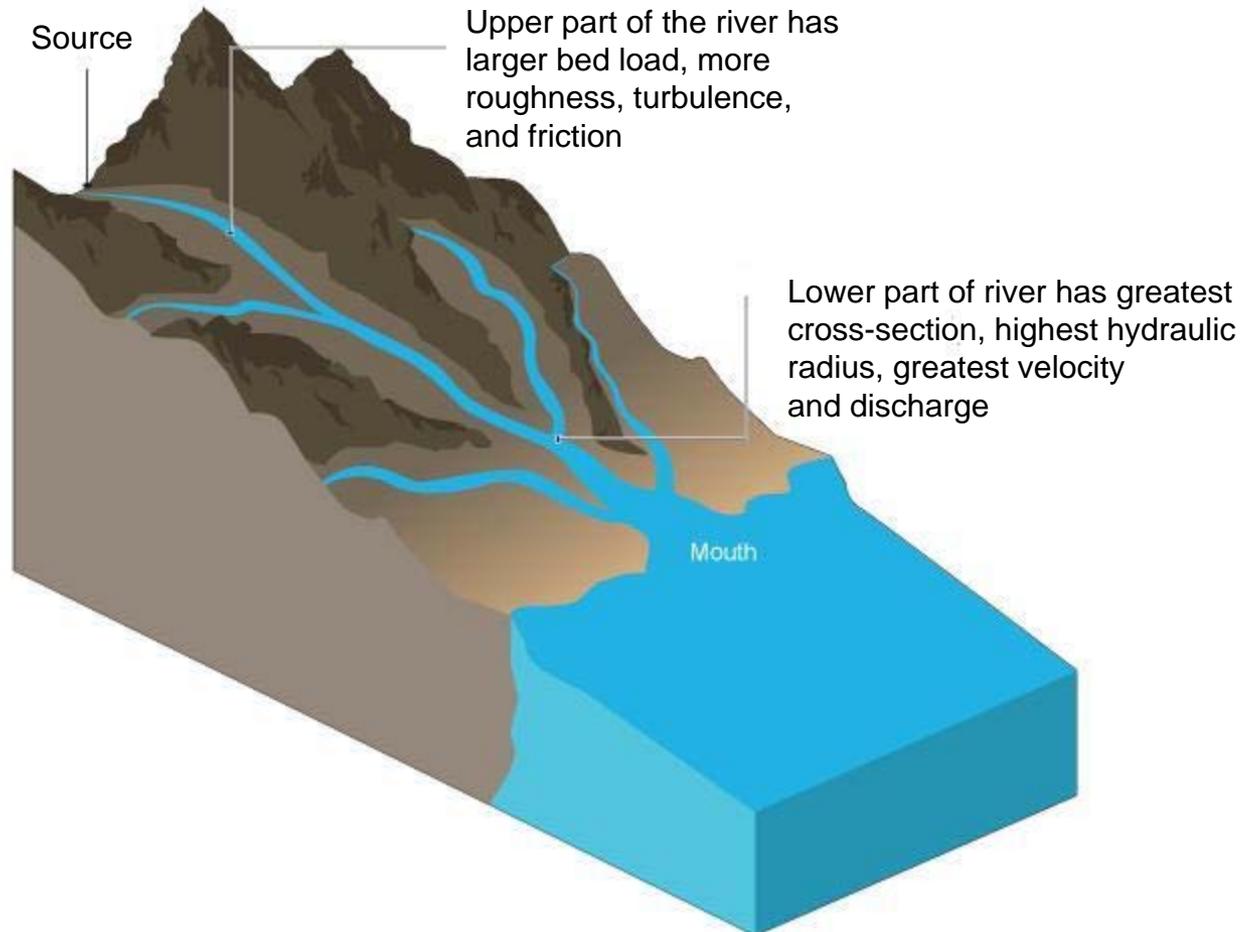
- 14. Hydroelectric Power: How it Works (Basic description with animation)

## Further Reading

- Electric Power Generation – A Non Technical Guide, Dave Barnett 2000 (*Ontario Power Generation, Video on Hydroelectric Generation*)
- Handbook of Applied Hydraulics, C. V. Davis and K. Sorenson
- Handbook of Applied Hydrology, Ven Te Chow
- Handbook of Hydroelectric Engineering, P. S. Nigam



# SITING HYDRO PLANTS



Source:

[http://www.bbc.co.uk/schools/gcsebitesize/geography/riverswater/river\\_profilesrev1.shtml](http://www.bbc.co.uk/schools/gcsebitesize/geography/riverswater/river_profilesrev1.shtml)

# Slide 5

## Siting Hydro Plants: Long Profile of a River

Typically, a stream or river falls more steeply at its head waters relative to its lower reaches. Thus, there is greater head available to be harnessed for power development in the upper reaches. However, suitable sites for large storage may be difficult to find in the upper reaches. In the middle and lower reaches, large impoundments may be possible but would require high dams to develop head. A large hydro plant typically needs a cascade of projects at different points to develop a river's available potential fully and effectively.

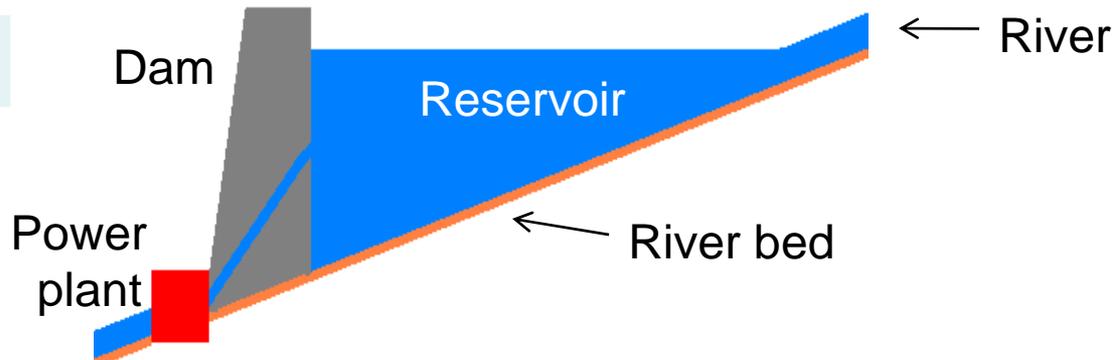
Decisions about where to put dams may raise potentially significant social issues such as relocation of large populations and submergence of agricultural lands. Selecting suitable sites for hydropower development therefore will require a balanced study of benefits and costs before a project can be implemented.



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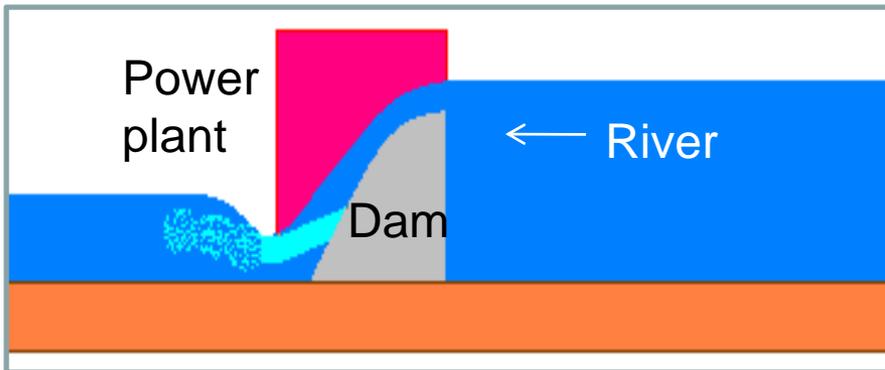
# CONVENTIONAL HYDROELECTRIC PROJECTS

## Storage Hydro

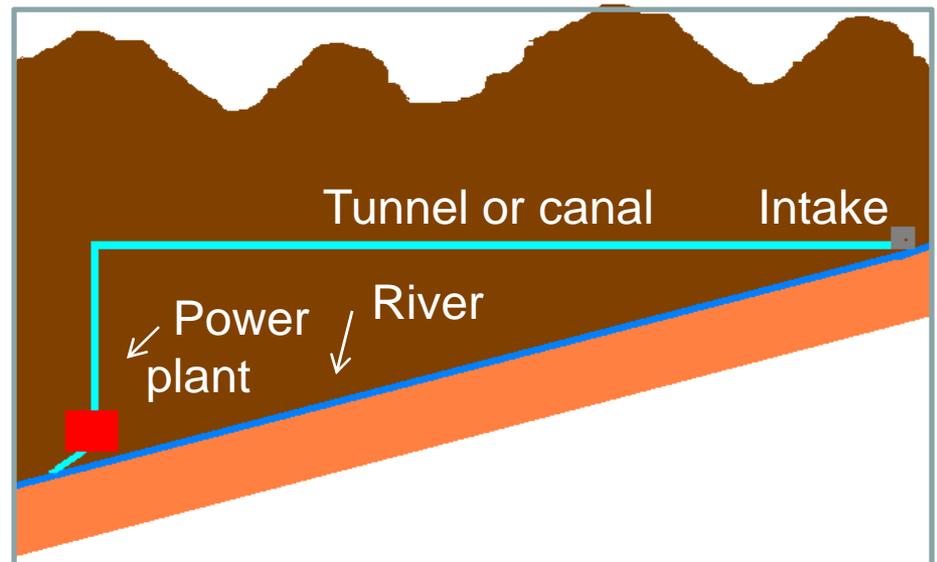


## Run-of-River Hydro

### Low head



### High head



# Slide 6

## Types of Hydroelectric Projects

As a river flows in its natural state, the energy of the water is dissipated by turbulence, heat, noise, and the transport of sand, rocks, and other solids. A conventional hydroelectric plant modifies the path of energy dissipation within a segment of the river so that most of the energy can be harnessed by a turbine. This is achieved either by completely stopping the water and creating a reservoir upstream of a dam, or by slowing it down and conveying it to the turbine via a smooth tunnel or canal at very gentle slope compared to that of the natural river.

### Conventional Hydro

There are two basic types of conventional hydropower plants:

**Storage Hydro** – Storage hydro is a hydro plant located downstream of a reservoir or a natural lake with controlled release. The river flows into the reservoir created by the dam and the hydro plant uses the water when it is most convenient to generate electricity. The difference in elevation usually is created by the reservoir.

**Run-of-River Hydro** – Run-of-river hydro refers to projects where there is no storage of water. The two most common arrangements are:

- The power plant and spillway are built across the river. Water goes through the power plant up to its maximum capacity and the excess goes over the spillway. Typically these plants are called “low head” because they capture only a small difference in water elevation.
- Some of the water from a river is diverted into a canal or a tunnel. After some distance, the water from the canal or tunnel is dropped vertically toward a hydro plant to generate electricity. Water is returned to the river below the power house. These plants usually capture a larger difference in water elevation and are called “high head” plants.

The vast majority of hydroelectric development consists of conventional plants, either storage or run-of-river hydro. Every project is different and the variety of designs is immense. Some projects occupy vast areas and include hundreds of separate structures, while others are hard to distinguish from a small house by the river. This is particularly true of very high head projects that can produce large amounts of power with very modest flows and therefore require small structures.

### References

- 66. Presentation from Hydro Quebec about its latest development, the Eastmain-Sarcelle Projects
- 123. Tennessee Valley Authority Hydropower Brochure
- 335. 1,000 MW Run-of-river Hydroelectric Power Plant at Toba
- 336. Brandywine Creek, Run-Of-River Hydroelectric Project
- 337. Ontario Power Generation, Video on Hydroelectric Generation
- 349. Ghazi Barotha Run-of-River Hydroelectric Project, Pakistan



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# SAMPLE HYDROELECTRIC PROJECTS



Itaipu Storage Hydro  
Brazil-Paraguay, 12,900 MW



Santa Rosa Run-of-River  
Hydro, Peru, 5 MW



Okinawa Pumped Storage  
(seawater), Japan, 30 MW

# Slide 7

## Sample Hydroelectric Plants

These images illustrate various types of conventional hydro facilities, and highlight the large range in size of hydro projects.

### Pumped Storage Hydro

Along with examples of storage hydro and run-of-river hydro, the slide also shows the Okinawa pumped storage facility, where moving water is available constantly because it is pumped to a higher reservoir during times of low demand, and then released to a lower reservoir at times of high demand to generate power.

Pumped storage plants do not produce net energy; they actually consume it because it takes roughly 25-30% more energy to pump water than the plant later generates with the same water. However, if the price differential between peak and off-peak power is more than 30%, pumped storage plants can become attractive. Very often the benefit comes primarily from the role pumped storage plants can play in maintaining stability of electrical frequency in large interconnected networks. When a large pumped storage plant is operating in pump mode it can reduce demand rapidly by stopping the pumps, and immediately add generation by reversing flow. This can make a difference of several thousand megawatts within a few minutes. For this reason pumped storage projects are, in accounting terms, more often considered to be assets of the transmission system than of the generation system.

There are several operational pumped storage plants around the world, so they are not unconventional in that sense. However, they are mostly practical in the United States, Europe, and other highly industrialized regions with very complex time-of-day tariff regimes for peak and off-peak power and a need to keep large amounts of power ready for frequency control.

### Photo credit:

- [www.itaipu.gov.br](http://www.itaipu.gov.br) – Itaipu Storage Hydro
- [www.iehydro.org/01-okinawa-seawater-pspp-lg](http://www.iehydro.org/01-okinawa-seawater-pspp-lg) – Okinawa Pumped Storage

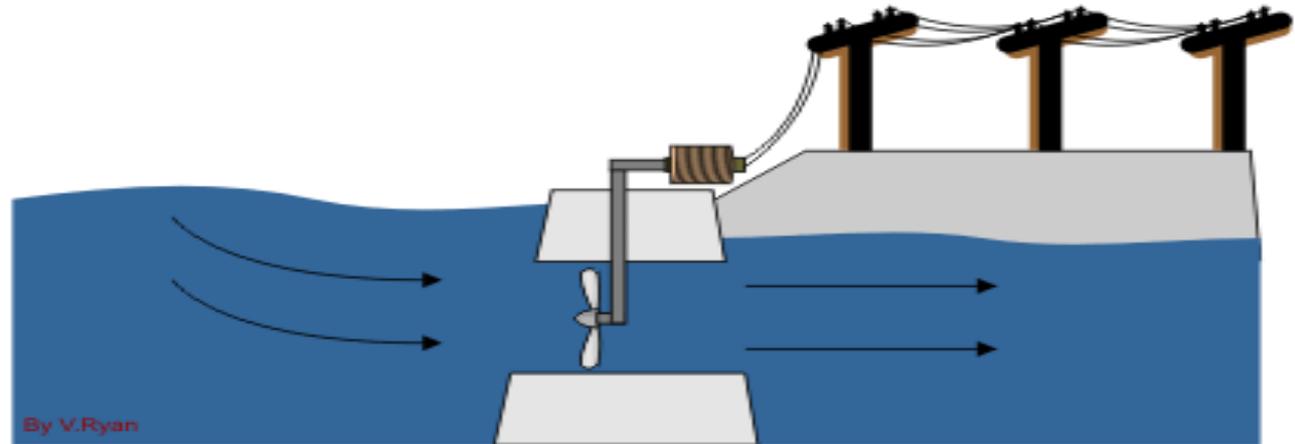
### References

- 338. Pumped Storage Plant
- 339. Hydroelectric Facts, Oldest and Largest Plants, Hydroelectric Countries



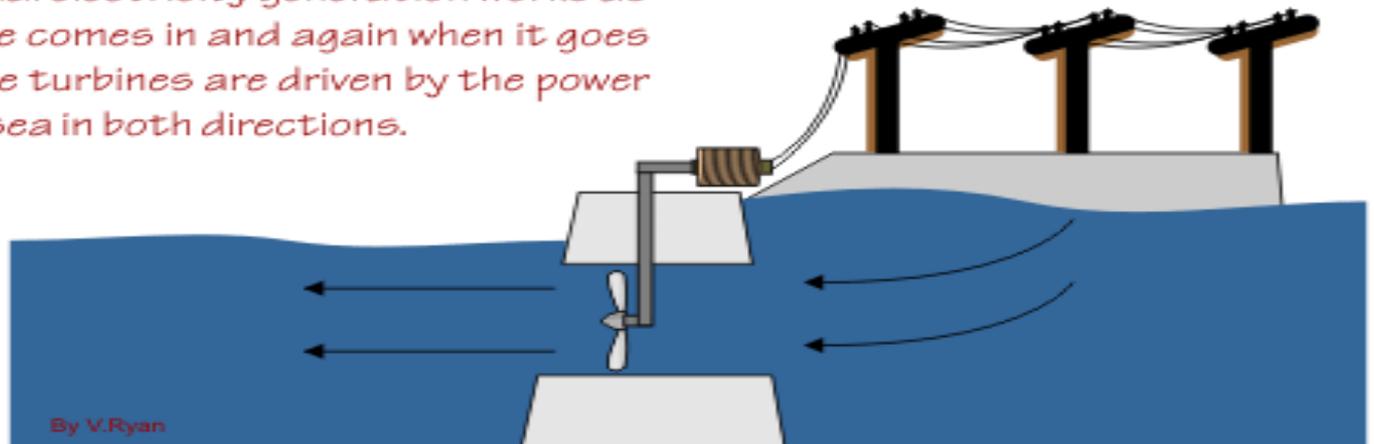
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# UNCONVENTIONAL HYDRO PROJECTS: TIDAL ENERGY



TIDE COMING IN

*This tidal electricity generation works as the tide comes in and again when it goes out. The turbines are driven by the power of the sea in both directions.*



TIDE GOING OUT

# Slide 8

## Unconventional Hydro Projects: Tidal Energy

Unconventional hydroelectric plants capture the energy from other forms of naturally moving water, such as the energy of tides, waves, or ocean currents. Hydro plants of this type are in the earliest stages of development, with the exception of a few tidal power plants. Tidal cycles limit generation hours per day so, by nature, tidal is a low capacity factor technology, rarely exceeding 35%. It is low head because tidal range is rarely above 15 m, so flows must be high, requiring large structures. In addition, the marine environment is very tough on all equipment and these power plants are exposed to severe weather. Thus, as a general rule, tidal energy is considerably more expensive than river hydro energy.

One of the few operational tidal power plants in the world is Annapolis Royal Tidal Power. Owned by Nova Scotia Power in Canada, Annapolis Royal started operations in 1983. It uses a single 7.6m diameter turbine on the Annapolis Basin, a sub-basin of the Bay of Fundy, which has one of the largest tidal ranges in the world. A rock-filled barrage carries a highway serving as a bridge across the bay, and also contains the powerhouse and sluice gates.

## Energy from Waves and Ocean Currents

There are many approaches to capture ocean wave energy, but all are in the experimental stage. Because of the low intensity of recoverable energy in waves, the technology may be attractive only to highly developed economies initially, due to high costs. Also, transmission issues appear quite formidable at present, and these projects may be difficult to insure because the risk of severe weather is high. RWE Innogy plans to construct a 4 MW wave power station off the Scottish coast in 2009, and Voith Hydro will deploy and test a 110 kV prototype turbine off the South Korean coast. These projects may provide useful data on costs and the energy potential of ocean current power generation technologies.

## References

- 340. Tidal Power
- 341. Seagen Shatters Tidal Generation Record

## Further Reading

- <http://www.masstech.org/cleanenergy/wavetidal/wave.htm>
- <http://home.clara.net/darvill/altenerg/tidal.htm>
- [http://images.google.com/images?sourceid=navclient&rlz=1T4SKPB\\_enUS327US327&q=wave+energy&um=1&ie=UTF-8&ei=6N1USqa3N4LbIAeGxN3eCA&sa=X&oi=image\\_result\\_group&ct=title&resnum=4](http://images.google.com/images?sourceid=navclient&rlz=1T4SKPB_enUS327US327&q=wave+energy&um=1&ie=UTF-8&ei=6N1USqa3N4LbIAeGxN3eCA&sa=X&oi=image_result_group&ct=title&resnum=4)
- <http://ocsenergy.anl.gov/guide/wave/index.cfm>



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# DISTINCTIVE ASPECTS OF HYDROPOWER

## UNIQUENESS

Each site results in a different project design

## DEPENDABILITY

Most hydroelectric projects have a “dependable capacity,” meaning that they can be used with confidence to meet peak demand for a specified time period

## COMPLEX but VERSATILE

Variability of flow and interdependence of flow, head, and storage result in complex planning but provides versatility of operation – water can be stored for use later as needed

# Slide 9

## Distinctive Aspects of Hydropower

### Uniqueness

Hydroelectric plants are unique in the sense that there are no two identical hydroelectric projects because the combination of topography, geology, and hydrology of a site defines a unique layout design for optimal development.

Hydroelectric plants are always adapted to the particular site. The disposition of different components to take best advantage of topography and geology is as much an art as it is a science. There are many possible configurations for any given site, so it is up to the layout engineer to identify a manageable number of options for detailed analysis and final selection. The equipment is designed and built for the best combination of head and flow so it is rare that a used hydroelectric turbine can be adapted for use at to operate on another site.

### Dependability

Most hydroelectric projects have some dependability, in the sense that they can be counted on to supply power at times of peak demand. Storage hydro has greater dependability than run-of-river hydro because the stored water can be used when it is most needed. Dependability is the main reason why hydroelectric power is so widespread.

The rising price of fossil fuels means a hydroelectric plant can be economically feasible just by displacing fossil fuel, even if another plant (fossil fuel/solar/wind) must be kept on stand-by to provide dependable power. Several decades ago fuel was much cheaper in relation to capital costs so it did not make sense to build hydro unless it could also displace the capital cost of other facilities. This analysis was done by calculating how much of the capacity of a hydroelectric plant could be considered dependable. Large and medium hydro development lost ground because of cheap fossil fuel. Today, many countries are looking at developing their untapped hydro resources and/or purchasing these resources from neighbors.

### Complexity

Most generation technologies have only one generation variable such as the fuel input (oil, natural gas, nuclear), the wind velocity, or the solar radiation intensity. Hydro has three mutually interdependent variables: flow, head, and available storage

Planning the operation of a storage hydro project in an interconnected system is much more complex than planning the operation of any other generation technology. A reservoir can be operated in different ways to provide different combinations of several objectives, including:

- Maximizing total annual energy production
- Maximizing dry season energy production
- Maximizing dry year energy production
- Maximizing instantaneous power output at times of maximum demand

In addition, when a reservoir is also used for irrigation, flood control, or other purposes, these objectives also must be included in operation guidelines. The optimization of these multiple and competing objectives becomes more complicated by the interdependence of flow, head, and storage – and also by the different hydrologic characteristics of the various plants in the system. Storage hydro, in particular, involves weighing various options and making trade-offs. If you try to maximize head by keeping the reservoir high, you run the risk of unexpected floods and then you waste water by spilling it. If you try to keep enough storage capacity to avoid spilling water, you lose head. If you try to maximize production, the reservoir could be emptied before the wet season starts, leaving the power plant with no firm energy or dependable capacity. If the head is low, the turbines operate very inefficiently and water is wasted.

Many large hydroelectric systems, including those in Brazil and China, use advanced mathematical optimization methods such as Discrete Differential Dynamic Programming (DDDP) to plan the operation of their hydroelectric plants, and many power markets use these methods to assign value to the water stored in hydroelectric reservoirs to make it comparable to the cost of fuel in thermal plants. In sophisticated pricing systems where hydro generators are left to decide their own dispatch (i.e., Argentina), savvy generators run their own models to anticipate periods of high prices and save their water for those times.

## References

- 16. Hydroelectric Power Evaluation: A Detailed Treatment of Hydro Benefits
- 342. Heuristic Algorithm with Simulation Model for Searching Optimal Reservoir Rule Curves



- Pico hydro – usually less than 5 kW
- Micro hydro – 100 kW or less (usually off grid)
- Small hydro – up to 5 MW (FERC – for licensing )  
– up to 20 MW (World Bank)  
(can be off grid or grid-connected)
- Medium hydro – up to 100 MW
- Large hydro > 100 MW

# Slide 10

## Hydro Project Classification

Although it is common to classify hydro projects based upon installed capacity into pico, micro, small, medium, and large projects, there are no universally accepted boundaries. Specific capacity limits often are established by governments or regulatory agencies to define projects that may qualify for special promotional pricing regimes and/or specific licensing requirements. The slide shows two different parameters of what constitutes a “small” hydro plant under US FERC regulations, as well as under World Bank guidelines. The distinction does not reflect project feasibility.

The difference between micro and small hydro lies more in the way the plant is designed and operated, rather than its size. Generally speaking, a micro hydro is a plant that is not expected to be interconnected to other plants in a grid. Therefore, the expectation of technical quality of the delivered power (voltage, frequency, flicker, and other characteristics that are highly controlled in interconnected systems) is not high and the plant can operate largely unattended, much like a small, isolated wind turbine. Such unattended operation is rarely practical above 1 MW. Most micro plants are less than 100 kW and are usually developed to supply a specific customer base, such as a village, lumber mills, or other small rural industries. Micro hydro plants typically use only a fraction of the available water in a river and are designed more on the basis of expected demand rather than on the optimization of the water resource. Unplanned/haphazard development of micro and small hydro plants in a river basin may compromise efficient use of river’s hydro potential.

## Connecting Small Hydro to the Grid

Unlike micro hydro, small hydro plants may be connected to the grid. There is little to differentiate a small hydro connected to the grid from a larger hydro plant, other than the scale of operation. Electrical protection and control systems to connect small hydro to the grid may be relatively more expensive (as a percentage of development cost) than for larger plants, and small plants offer less in the way of frequency stabilization. While larger hydro plants are ideal sources of spinning reserve (the margin between the load and the full capacity of each generating unit) for system operators, a dispatcher may tell a small hydro not to bother to keep that margin and just run flat out. Therefore, in systems that pay for spinning reserve (bundled in a category of compensation called “ancillary services”), small hydro may not qualify for that payment.

On the other hand, a small hydro facility may not need to comply with some rules designed for larger generators. In practice, all operators need to communicate with dispatchers regularly and agree on an hourly generation schedule. But in the case of small hydro plants, dispatchers in some systems may just give the operator a long-term instruction and not require the operator to file a specific generation schedule, since the contribution of the small hydro is not significant relative to normal changes in demand. A small hydro operator might not even be required to notify the dispatcher before synchronizing its turbines to the grid.



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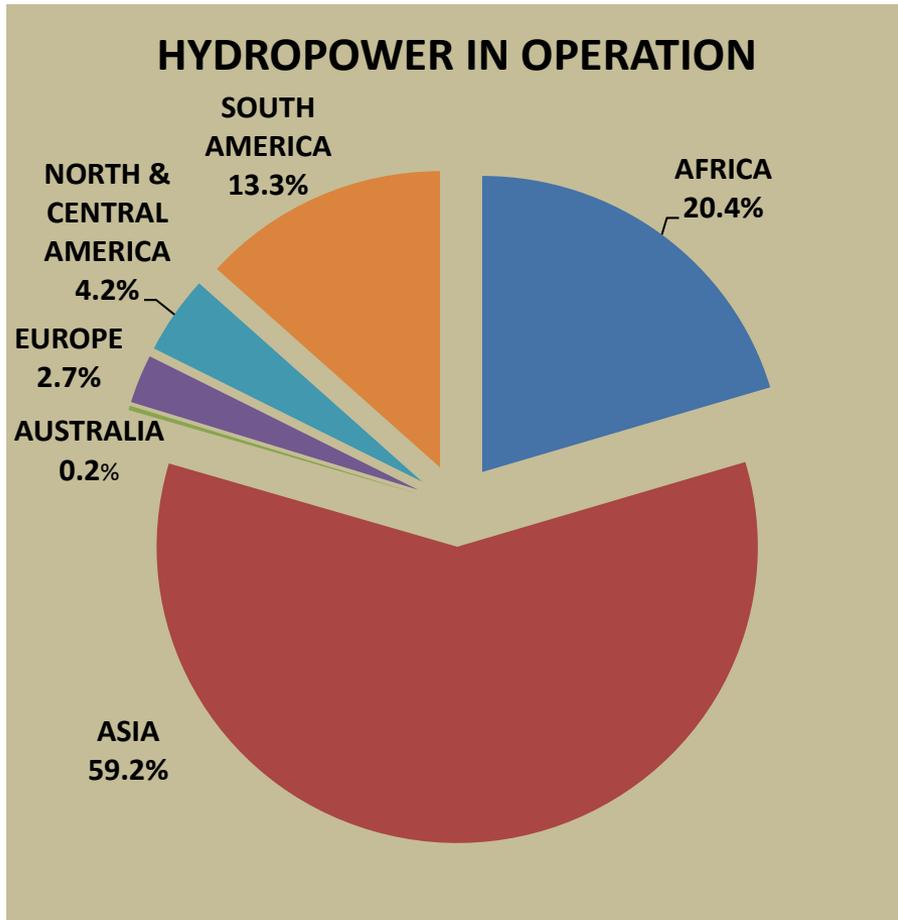
# PRESENTATION

- Technology Overview
- **Global Status**
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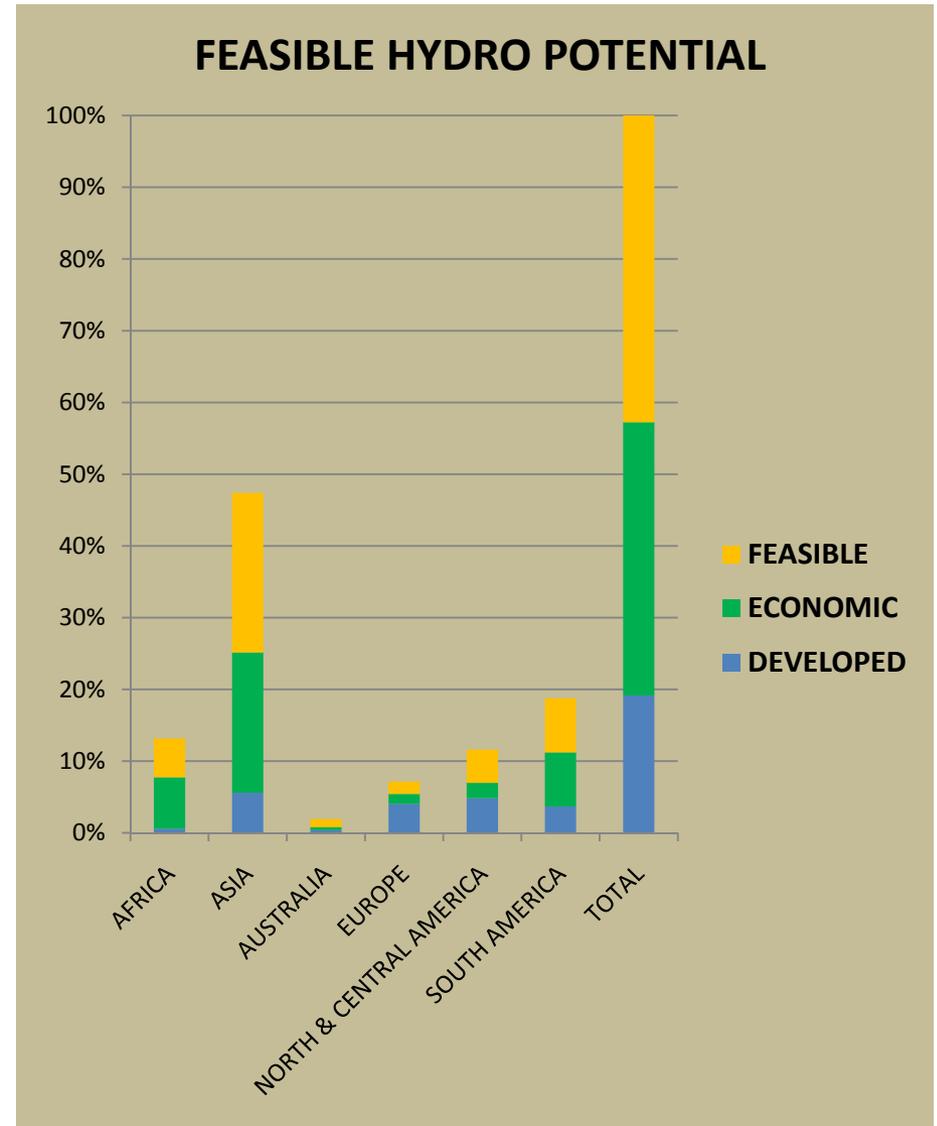
# Slide 11

## Global Status

# WORLDWIDE HYDROPOWER



**HYDROPOWER ACCOUNTS FOR 20% OF WORLDWIDE ELECTRICITY SUPPLY**



# Slide 12

## Worldwide Hydropower

Hydroelectric power currently accounts for about 20% of global electricity supply, with more than 600,000 MW of installed capacity. Hydroelectric power supplies more than 50 percent of national electricity in about 65 countries, and more than 80 percent in 32 countries. The theoretical potential of hydroelectric power is immense because it includes all the energy released by rivers on their way to the sea. However, only about one-third of that theoretical energy potential can be considered technically feasible to harness for hydropower, because of geology, topography, and climate conditions. Even a lesser portion of the potential may be harnessed in an economical manner.

<b>Region</b>	<b>Technically Feasible</b>	<b>Economically Feasible</b>
Africa	1,750 TWh/yr	1,000 TWh/yr
Asia	6,800 TWh/yr	3,600 TWh/yr
North/Central America	1,660 TWh/yr	1,000 TWh/yr
South America	2,665 TWh/yr	1,600 TWh/yr

1 TWh (terawatt hour) = 1 million MWh

Of the technically feasible hydro potential, only about 20 percent has already been developed. An additional 35 percent should be economically feasible to develop under current costs and energy price conditions. The rest is still too expensive to develop but may become economically feasible as fuels and other generation alternatives become more expensive in the future.

## References

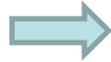
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# HYDRO MARKETS

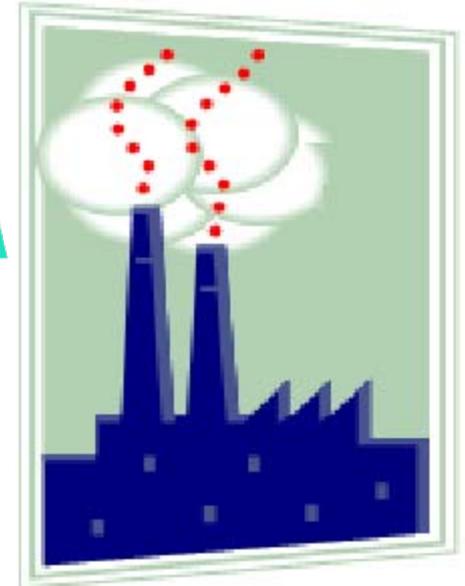
Abundant  
Precipitation



Mountainous  
Terrain



High Electricity  
Demand



**ACTIVE HYDRO MARKET**

# Slide 13

## Hydro Markets

Until the early 1990s, most hydroelectric development was carried out by government agencies or, particularly in the United States, by investor-owned public utilities. In many parts of the world government agencies are still the primary developers, however, after the advent of independent power producers and the restructuring of power sectors worldwide, many private-sector companies started developing hydroelectric projects. Today, the private hydropower development industry is very dynamic, with a large number of developers from all parts of the world competing to obtain permits and build hydroelectric plants of every scale.

Based upon geographic region, here is a brief description of current trends in hydro development:

**Asia:** The most dynamic markets today are in China and Southeast Asia. China and Vietnam develop hydro for their own needs, while Laos and Cambodia have more than 100 projects under development, with much of the output destined for export to Thailand and Vietnam. Nepal and Bhutan are developing hydro to supply India. Tajikistan and Kyrgyzstan have ambitious plans to develop large hydro for export to Pakistan and other countries.

**North and South America:** Most countries have active hydro markets but Brazil, Peru, Colombia and Panama are the most dynamic. In Canada, only Quebec continues to actively develop large-scale hydro. Very little new hydro is being developed in the United States, but there are many projects undergoing updating through rehabilitation or repowering.

**Europe and Near East:** Most hydro in Europe has been developed and environmental restrictions and land limitations prevent further development. Turkey has recently increased its hydro development under market terms and is actively developing more than 20 sites.

**Africa:** There are several medium-large size projects underway in Africa, but very few are market driven as the tariff regimes are still heavily subsidized and do not enable cost recovery.

## References

- 343. Abundant Hydroelectric Potential Lures Corporations to the Mekong River

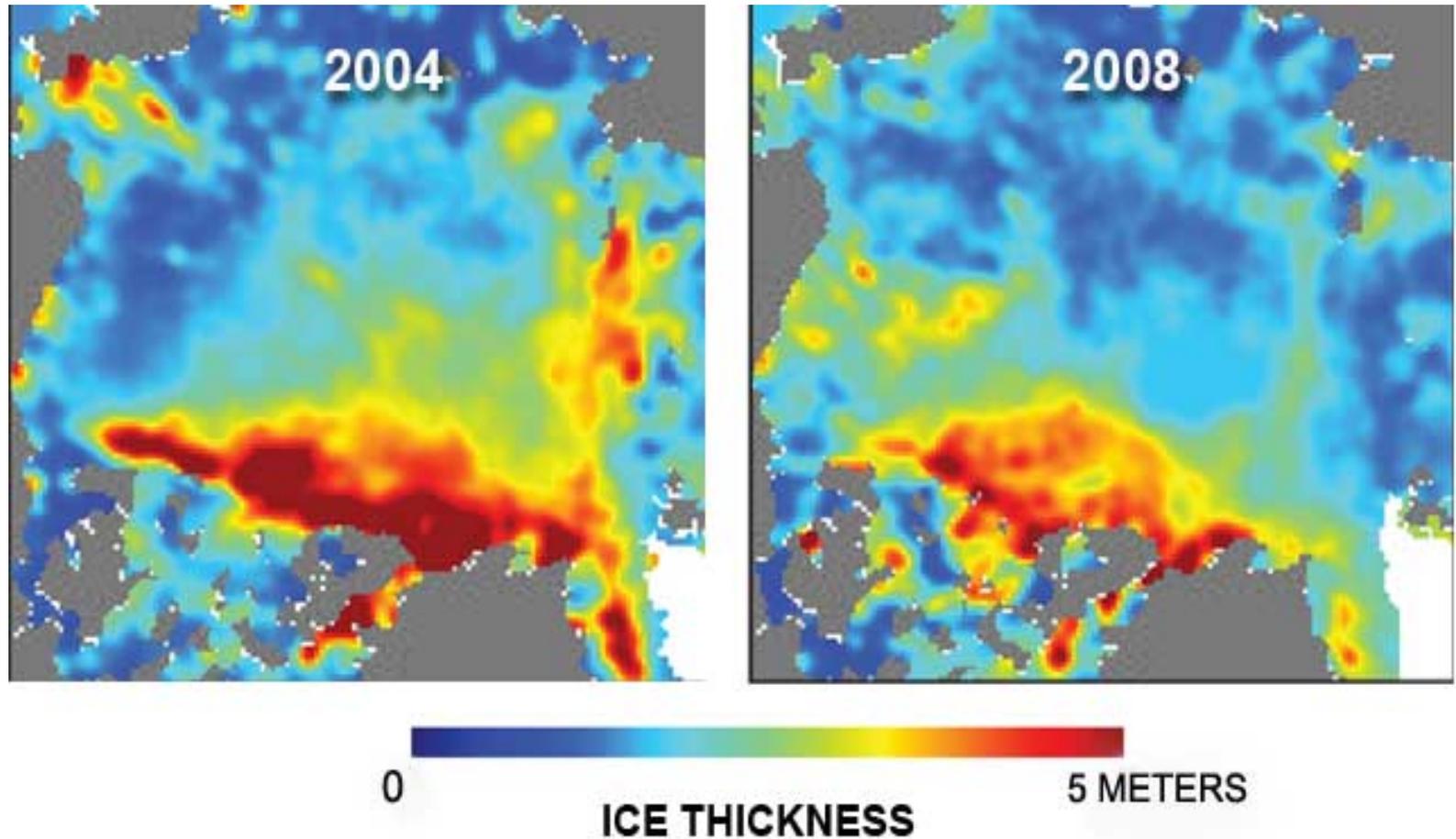
## Further Reading

- *Global Hydro Energy Markets – Key Trends and Challenges, (Abstract of Worldwide Market Compendium, Published: 2008/07)*, <http://www.the-infoshop.com/study/labd70429-hydro-energy.html>



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# CLIMATE CHANGE: ARCTIC OCEAN ICE CAP CHANGES



Source: <http://www.jpl.nasa.gov/news/news.cfm?release=2009-107>

# Slide 14

## Climate Change

An emerging issue for hydroelectric projects is the effect of global climate change on the hydrologic cycle. Currently, there is very little capability to provide quantitative projections of changes in precipitation and streamflow at the river basin scale due to limited observations and significant uncertainties in modeling processes. From a conceptual and theoretical hydrologic perspective, global warming should, on average, accelerate the hydrologic cycle. In higher temperatures, evaporation and the atmosphere's water-holding capacity should increase, leading to an increase in climate variability with more intense precipitation events or droughts. As temperatures increase, the likelihood of precipitation in the form of snow will decrease, which will result in earlier melt and less river volume during the melt season. Thus, it is likely that the seasonality of rivers may change, with different water flow at certain times of the year, compared to previous years.

A second issue of interest is that of glacier melt. In snowmelt-fed and glacier-melt river basins such as the Hindu-Kush-Himalayas (HKH), there is increased risk of reduced river flows or drought. To the extent that a river basin has glaciers, a reduction of glacier volume may result in flows that are augmented by non-renewable ice melt, distorting the perception of long-term average flow. After the glacier melts completely, such non-renewable ice melt will disappear from the river flow and if precipitation patterns remain the same, then average annual flows could return to the lower pre-melt condition. If, despite glacier meltdown, the precipitation in the watershed remains the same both in quantity and distribution, then less water will remain locked up as snow or ice during the winter. This will result in a more uniform (i.e., less seasonal) flow that may be favorable to hydropower production.

Factors influencing water availability, which include climate change, land-use changes in the watershed, upstream diversions, competing uses of water, population increase, desertification and environmental degradation, significant water policy changes and a host of other elements, are dealt with on a case-by-case basis during a hydro project's feasibility studies. Statistical probabilities of long periods of low river flows are calculated to estimate minimum reliable generation potential. For large storage reservoirs, rules specifying withdrawal amounts are developed to ensure that reservoirs are not emptied during long dry spells. For run-of-river projects, hydropower investors sometimes take insurance to cover sustained low-flow periods to meet debt service requirements. The potential effect of climate change on extreme flows may be addressed by existing design approaches (see dam safety slide).

Increased sediment transport in a river because of glacier meltdown has not been specifically identified as a concern at this time. However, increased sediment flow is possible if glacial meltdown exposes soft material in the river catchment to heavy rains. Also, if the glacial meltdown was sudden, creating glacial lakes which gave way to severe floods (Glacial Lake Outburst Floods), significant sediment transport and landslides may result.

As scientific data emerges on the impact of climate change and the effects become more defined, guidelines and mechanisms to address these effects will need to be developed and hydroelectric designers must take such phenomena into account during project design.

## Glacial Lake Outburst Floods

Global climatic change during the first half of the 20th century has had a tremendous impact on the high mountainous glacial environment. Rapid melting of glaciers led to an increasing number of glacial lakes, which pose a significant threat

to lives and livelihoods along the rivers due to high potential for outburst floods. Due to the faster rate of ice and snow melting, the accumulation of water in these lakes can increase rapidly and result in the sudden discharge of large volumes of water and debris, causing flooding downstream if the moraine dams break. Glacial lake outburst floods (GLOF) lead to very high speed flood waves downstream, which may result in significant loss of life and destruction of valuable forests, farms, and infrastructure.

In South Asia, particularly in the Himalayan region, the occurrence of GLOF events has been on the rise. The catastrophic 1985 GLOF event in Nepal known as the Dig Tsho GLOF destroyed the \$1.5 million Namche small hydro project. UNEP, through its Environment Assessment Program for Asia-Pacific (UNEP-AP), is trying to establish an operational early warning system to monitor GLOF hazards in the HKH region. EAP-AP will implement the project in collaboration with the International Center for Integrated Mountain Development (ICIMOD), Nepal. USAID is working with NASA and ICIMOD on glacier identification and change analysis in HKH, linking snowmelt and glacier melt to flooding in the Ganges-Brahmaputra-Meghna river basin. Monitoring of GLOF is very difficult due to limited access and increased number of events. Near-real time monitoring does not appear feasible, either.

However, accurate and timely information on the spatial locations and continuous monitoring of current glacier lakes and formation of new ones are necessary, to identify potential hazards and to devise means to lessen downstream impact. Remote Sensing technology could play a lead role in identifying potential risk lakes and monitoring the potential for GLOF. Analytical tools will need to be developed to model GLOF hazard scenarios and to predict impacts.

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# EXTENDING THE LIFE OF HYDRO PROJECTS

- Rehabilitation
- Repowering
- Catchment increase
- Regulation
- Storage recovery
- Reregulation



# Slide 15

## Extending the Life of Hydro Projects

Hydroelectric projects have a very long life span. During that time the needs of the power system can change. There also can be changes in the river catchment that modify the characteristics of the arriving flow, including the installation of newer hydroelectric plants upstream. It is hard to gauge exactly how long a large concrete dam will last but there are dams that are already more than 100 years old. With proper maintenance and periodic replacement of equipment, a hydroelectric project could last centuries. Thus, it is very common to see investments to extend the operational life of existing hydro facilities, to maximize the value of the project under changing conditions of the regulatory framework and the system in which it operates.

Typically, as the value of hydroelectric power to the system increases, operators may find it attractive to increase the flow at the site by diverting water from neighboring rivers by means of dams, tunnels, or canals. These circumstances, together with the need to periodically replace worn equipment, determine many types of possible upgrades or rehabilitation to a hydroelectric power plant. Some of the common updates to an existing project include:

**Rehabilitation** – Refers to repairs or replacement of equipment and civil works to extend the life of the project or to recover capacity that may have been lost due to deteriorated equipment. This may also involve dredging the reservoir to recover storage volume that may have been lost to sediment deposition.

**Repowering** – Refers to the increase of installed capacity or efficiency of a project. This may involve replacement or addition of generating equipment to increase the energy production and the dependable capacity of an existing project. Sometimes repowering is combined with an increase in head achieved by raising the crest of a dam so that higher reservoir levels and storage are possible, resulting in more energy production.

**Catchment Increase** – Refers to the increase in inflows by diverting water from neighboring river basins by means of dams, tunnels, or canals so that more water is available to the hydro project.

**Regulation** – Refers to the addition of upstream storage. This can be done to reduce spill and increase generation using the same water, but often the goal is to obtain greater flexibility so that generation can be maximized during the hours when electricity prices are higher. Very often, the development of a new hydro project upstream provides this added regulation.

**Storage Recovery** – Refers to the recovery of live storage lost to sediment deposition. This is achieved by dredging or by flushing sediment through bottom outlets during high flow season.

**Re-regulation** – Refers to the addition of downstream storage. This is necessary when it is desirable to maximize operation during peak hours, but such short-term increases in flow can have a negative downstream impact. A storage reservoir is built downstream to regulate turbine flows so that downstream impact is minimized.

There are a number of examples of older facilities being renovated for continued or expanded generation:

### Corani-Santa Isabel Catchment Increase

This Bolivian power facility, built during the 1960s, consists of two cascading plants, each with nearly 1 km of head. Such high heads mean that enormous power is generated by very small amounts of water. Ever since its development, the project has been capturing water by diverting small streams and creeks of neighboring basins through a network of tunnels and canals that currently extends for more than 100 kilometers.

## **Paute Storage Recovery**

A major landslide in 1989 caused a considerable loss of storage in the reservoir of Paute, the primary source of electric power in Ecuador. An extensive recovery project was undertaken requiring specially built barges and other equipment to remove millions of tons of sediment that were blocking the intakes to its turbines.

## **Canon del Pato Regulation**

Canon del Pato in Peru was acquired by Duke Energy during the privatization of Electroperu. The new owners evaluated the pricing regime and determined that additional revenue could be obtained by short-term flow regulation that would allow more water to be used during peak hours. Since there was no suitable location for a reservoir, two narrow storage basins were built at the sides of the river upstream of the plant, using rock embankments and a rubber membrane lining.

## **El Chocon Re-regulation**

During the 1970s, Argentina built its first large-scale hydroelectric development, El Chocon, in northern Patagonia. The peaking operation of the plant resulted in complaints by downstream farmers about damaged irrigation intakes and drowned livestock. A re-regulating reservoir was built and fitted with a small hydro power plant, Arroyito, to mitigate these problems.

**Photo credit:** NREL

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# PRESENTATION

- Technology Overview
- Global Status
- **Hydro Economics**
- Technical Issues & Solutions
- Best Practices

# Slide 16

## Hydro Economics



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# HYDRO CAPITAL COSTS

**Poor Site**  
**\$4,000/kW**



THE COST OF A HYDRO PROJECT  
IS HIGHLY DEPENDENT ON SITE  
CONDITIONS

**Good Site**  
**\$800/kW**



# Slide 17

## Hydro Capital Costs

Hydro development costs are front-loaded, meaning that the investment required for construction of the initial project is high. However, hydro plants have very low operation and maintenance costs since, unlike fossil fuel plants, there is no fuel cost to run the plants. Typically, power generating machinery accounts for only about one-third of the investment in a hydro project; the rest is invested in civil works, engineering and environmental studies, and specialized field surveys; and environmental enhancements and mitigation. In some cases, resettlement costs might be involved. Hydro costs are highly site specific and are affected by numerous parameters, making cost generalizations very difficult.

Among the many factors that affect the cost of a project are site topography, rock quality, availability of access roads, distance to the interconnected grid, earthquake risk, and sediment load in the river. Of course, hydrology and local cost of labor, cement, steel, and explosives also must be factored into the cost equation. Recent improvements in tunnel-boring technologies are giving some advantages to projects using tunnels rather than dams to develop head.

As a rule, hydro project capital costs usually fall in a range between \$800/kW and \$4,000/kW. Economies of scale are important, so a small project could cost more per unit than a medium-sized project. (Small run-of-river projects that rely on local labor and competitive bids for equipment can be very cost-effective investments, with per unit costs at the bottom of this scale). An average cost for medium-size projects in the 100 to 400 MW range is around \$2,200/kW (in 2009 dollars). The unit cost does not include "soft costs" (legal costs involved in all the contracting and licensing) or IDC (interest on capital during construction). Annual operation and maintenance (O&M) costs generally are between 0.5% and 1% of the capital cost.

However, the cost per kilowatt is not a very good indicator of the likely economic performance of a hydro project because it does not say anything about how much energy will be obtained from one installed kilowatt. It could be that in one year each kilowatt produces 8,760 kWh (100% capacity factor), or it may produce only 876 kWh (10% capacity factor), depending on the amount of water available for generation, which in turn depends on river flow and the storage available. Thus, the cost of producing one kWh of energy is a useful parameter to assess the economic attractiveness of a hydro project.

Unfortunately, no generalizations really are possible since the cost of energy production is quite independent of plant type and is not strongly related to scale. The one factor that seems to correlate well with energy production cost is the capacity factor. This is rather obvious in that the more energy one gets for a given amount of installed capacity, the cheaper that energy will be. However, this does not mean that only high CF projects are cost effective. In some systems, peak power is highly prized, so a low CF may be more profitable even if the average cost of energy is higher. Also, the secondary benefits of hydro may significantly improve the attractiveness of a specific project.

Many large hydroelectric projects are not built solely on the basis of power generation economics. In the case of international projects such as Yacyreta and others in the Plata River Basin, other considerations, including cross-border political cooperation and trade are involved. (The Yacyreta hydro plant, a 50:50 joint venture between Argentina and Paraguay, has numerous dams and facilities on which over \$7 billion has been spent to date). In other cases, energy independence is a primary motivation for hydro projects. In some landlocked countries of Central Asia (Kyrgyz Republic, Tajikistan) or Africa, for instance, a hydroelectric project may be the only large-scale means of energy independence if the countries do not have domestic fuels and depend on their neighbors for supply.

## **Small and Micro Hydro Projects**

Per unit of energy generated, a small hydro facility may cost more than a large hydro and a micro hydro plant may be even more expensive if all costs (including investment costs) are fully taken into account. Nevertheless, in some rural locations, such projects may be the only viable sources of long-term power. Because operating costs of these projects may be low and affordable to communities, many governments and donors find such projects attractive as catalysts for rural economic growth. Depending on funding issues, small and micro-hydro projects generally can be brought online fairly quickly, with the initial project investigation and licensing stages completed in perhaps two years, and the actual construction taking another two years.

For small and micro hydro plants located far from the main grid, transmission costs may be significant, similar to comparable solar and wind generation access costs. Typically, small and micro hydro plants are developed to supply off-grid consumers. Nevertheless, if several such projects are feasible in a geographic area, electrical interconnection of these projects may be considered along with connections to the grid to improve reliability and overall efficiency of operation. Such interconnections are usually planned by the national utility or energy planning ministry and funded accordingly.

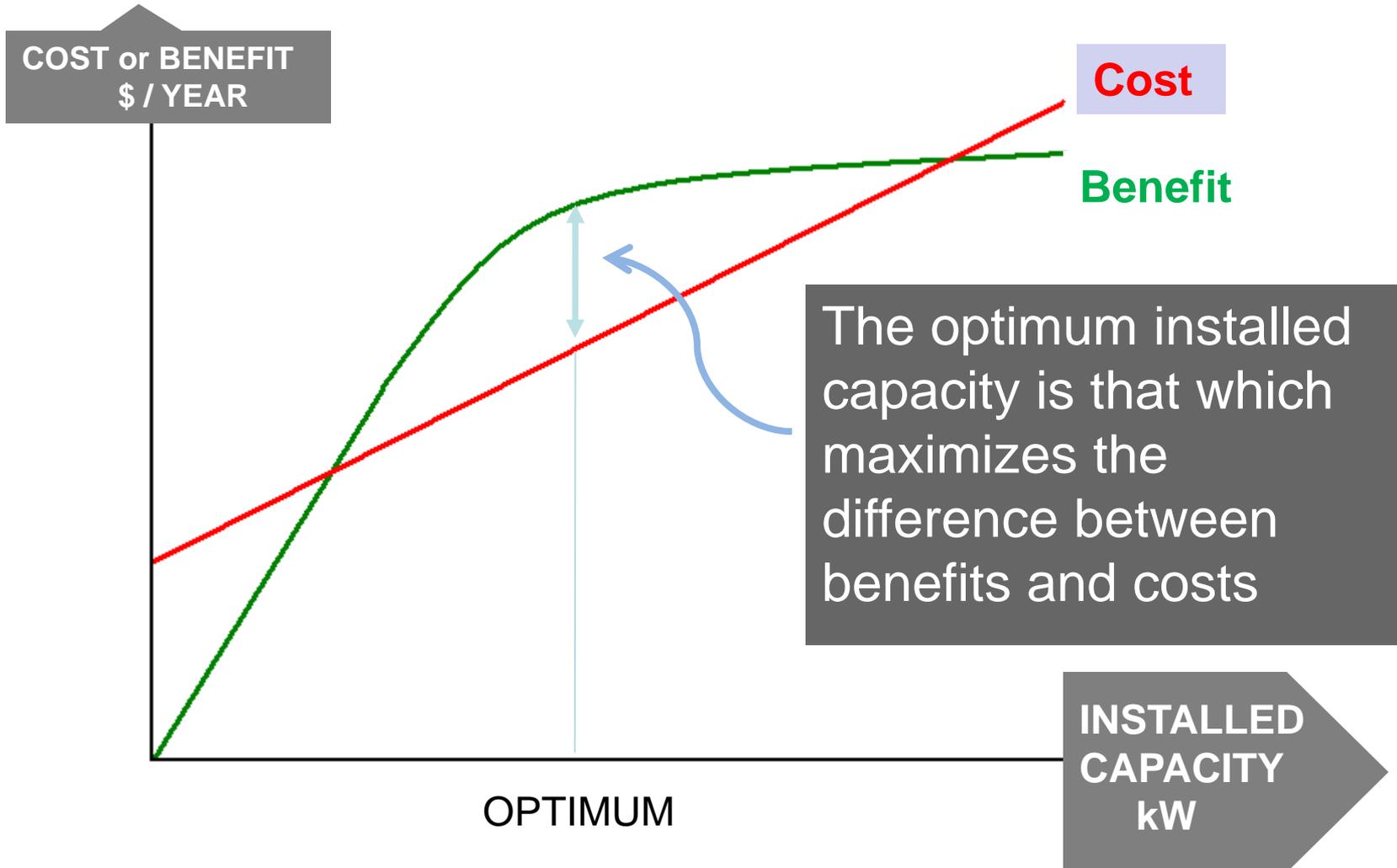
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# THE IMPORTANCE OF SIZE



# Slide 18

## Hydro Size and Cost

The cost of a hydro plant is nearly directly proportional to its installed capacity but it is not zero when the installed capacity is zero because there are many civil works that need to be built just to put one kilowatt of capacity in service.

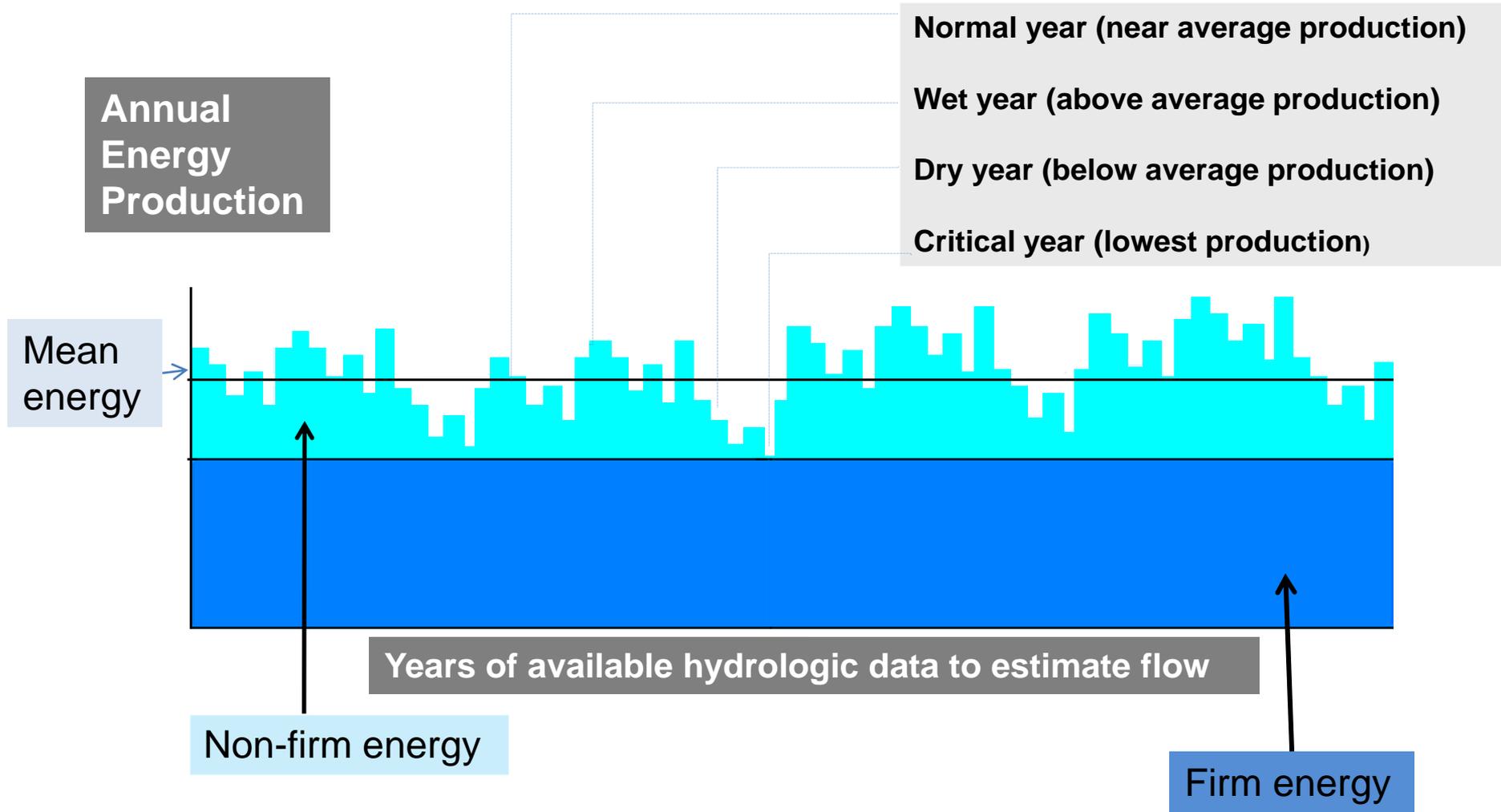
As capacity increases initially, the benefits rise linearly because at low levels of capacity there is enough water to make use of every additional kilowatt at all times. After a certain point, there is not enough water all the time to make use of additional kilowatts. Thereafter, the incremental benefits start to decrease until the incremental benefits of additional capacity are very small.

The optimum installed capacity is that which maximizes the expected difference between benefits and costs. It is very important to select the correct size of the plant in relation to the characteristics of the market it will serve.

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# HYDRO ENERGY PRODUCTION AND SYSTEM BENEFITS



# Slide 19

## Hydro Energy Production and System Benefits

Hydro projects potentially offer multiple benefits to the electricity system as well as to the population of the surrounding area. Benefits to the system (aside from a reliable source of power generation) include frequency control and other stabilizing measures (particularly from large plants). Surrounding areas may enjoy improved water supply and irrigation, regulated downstream flows, and recreation and tourism opportunities. Recreation benefits may be more significant in locations easily accessible from large metropolitan areas. In developed countries, hydro owners generally are required to provide access to the project waters and to provide certain minimum recreation facilities as part of project development. This idea is catching on in private development in other parts of the world. Typically, private power generators (and sometimes government-owned utilities) develop facilities around hydro project lakes for tourism.

The benefits to the electricity system of a hydroelectric project depend primarily on three key measures of its expected power production: mean energy; firm energy; and dependable capacity. Payments from the system to the hydro operator will be based upon these measures.

**Mean energy** is an estimate of average annual energy production of a hydro plant if historical river flows were repeated. The estimate is derived by simulating proposed plant operation using historical flows. Energy generation is usually denoted in kWh (kilowatt hour – one unit) or its multiples – MWh (1,000 kWh), or GWh (1 million kWh).

**Firm energy** is the amount of energy guaranteed to be available at a given time. The definition of firm energy of a hydro plant is often dictated by the system requirement for such guaranteed energy. Typically, firm energy from a hydro power plant may be defined as the energy that could be generated by the plant during low flow sequences with statistically defined frequency (e.g., one in 10 year low flows). Such hydro energy is considered to have the same reliability as energy produced by a conventional thermal plant operating in the same electrical system.

The difference between mean energy and firm energy is called secondary energy, or non-firm energy, and is particularly important in the design and negotiation of power contracts. Non-firm energy refers to all available energy above and beyond firm energy.

Energy benefits of both firm and non-firm energy are measured in terms of the fuel and other variable operating costs that would otherwise be required to produce that amount of energy by the least expensive technically feasible thermal alternative.

**Dependable capacity** is the portion of the installed capacity of a hydroelectric plant that can be counted on to meet the peak load of the system with the same confidence as that of a conventional thermal plant. To determine dependable capacity it is necessary to estimate how the firm energy can be used to meet as much of the peak demand as possible. Secondary or non-firm energy does not contribute to dependable capacity.

Capacity benefits are measured in terms of the capital cost and other fixed costs that would otherwise be required in obtaining the same amount of capacity by the least expensive technically feasible thermal alternative. Conceptually simple, dependable capacity's economic value in terms of thermal alternatives is universally accepted. However, the actual allocation of quantities and prices of dependable capacity of a hydroelectric project for commercial purposes is a matter of

regulatory policy. In many systems determining dependable capacity is subject to very complex calculations, different approaches, and considerable dispute. In 1989, for example, a lawsuit for almost \$100 million was filed in US federal court by a power utility in South Carolina claiming that a contract signed 40 years earlier overestimated the amount of dependable capacity of a hydroelectric project.

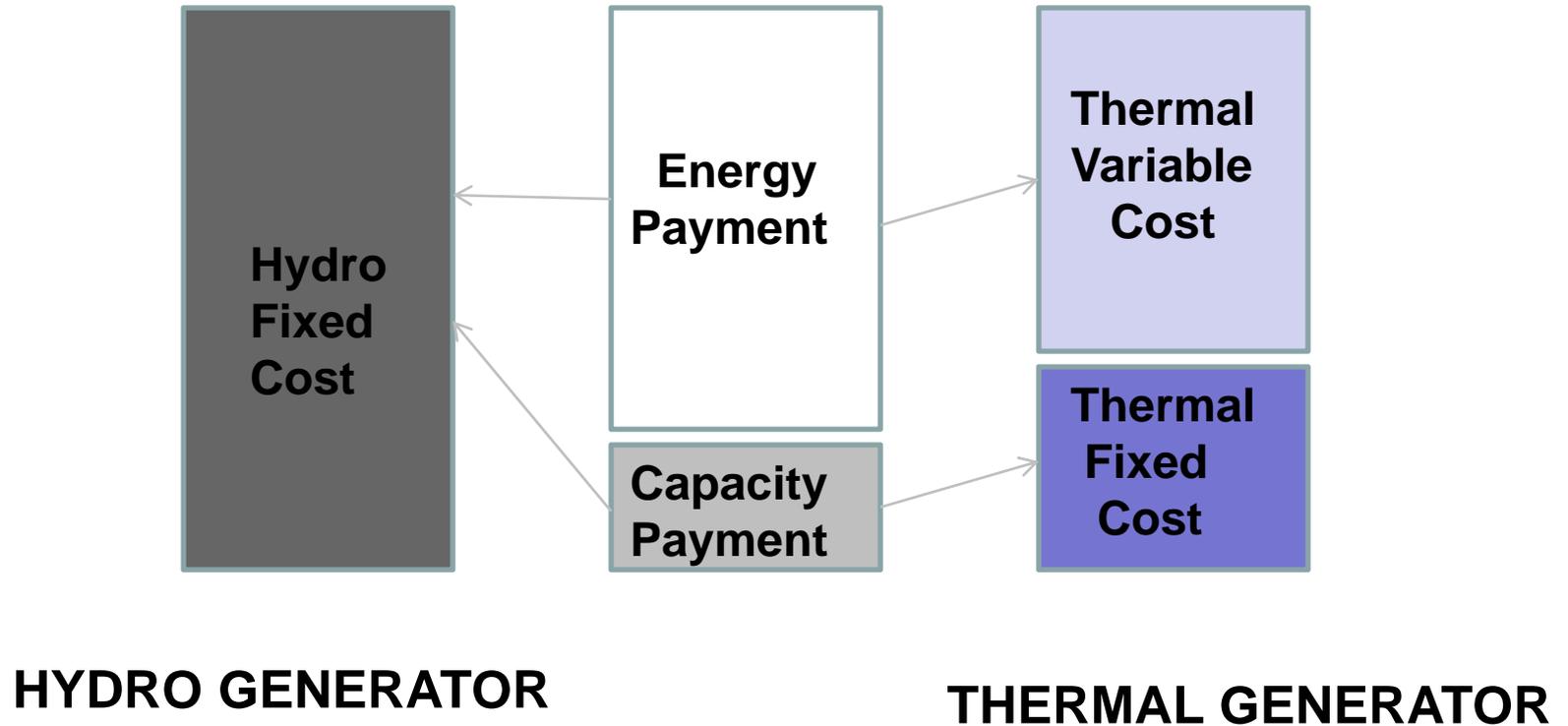
One of the most vexing problems of hydro developers in several markets is to anticipate the revenue from capacity sales as allowed by regulatory agencies. This often results in modifications of design to introduce features that, within applicable regulation, increase the level of dependable capacity.

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- 347. FERC – Hydropower Licensing
- 348. FERC – Recreation Development at Licensed Hydropower Projects



## Typical Power Market Pricing System



# Slide 20

## Hydro Revenue Streams

Because of hydro's long period of development and the large up-front investment required, many governments have found it necessary to offer incentives and well-defined long-term stability and risk management to attract private investment in hydro projects.

In planned systems, which are common in many developing countries, private investments for hydro projects are secured through defined licenses for individual project development and power purchase agreements (PPA) that define the quantity, quality, and timing of power purchase and the price to be paid for project generation power over a fixed term (usually 25-30 years). The licenses and PPAs collectively try to address major risks by providing for guaranteed power purchase and payments, non-nationalization of assets for the term of the project, and non-discriminatory treatment of foreign and local investment.

Large amounts of private hydro investment have poured into many Asian countries (e.g., Bhutan, India, Tajikistan, Laos PDR, Nepal, Pakistan, Sri Lanka, Tajikistan, and Turkey), in the last two decades. Public-private partnership (PPP) investments are also on the rise, including government as an equity investor (Laos PDR, Nepal). Competitive bidding as well as negotiated PPAs have been successfully developed for hydro projects in many Asian countries. Since most of these countries have major power deficits, pricing for new power is based on the cost of alternative power, which is usually fossil fuel generation. Through bilateral (Georgia, Nepal, Afghanistan) and regional programs (Regional Energy Markets Assistance Program and South Asia Regional Initiative for Energy), USAID has facilitated development of enabling environments, regulatory regimes, and private investments in hydro and other power projects.

## Market-Driven Systems

In sophisticated market-driven systems (particularly in Latin America, the EU, and some US states), payment for hydro is based on market needs and prices are not guaranteed by long-term PPAs. These systems are regulated by independent entities that focus on lowest cost to the consumer while providing open market access to any investor. When there is no contract or power purchase agreement (PPA) these payments are either regulated or are established by certain provisions in what is known as marginal cost pricing.

In marginal cost pricing systems, a merchant generator (i.e., one that does not have a contract) receives (variable) payments for energy delivered and (fixed) payments for capacity contributed, usually based on dependable capacity. These payments are based on the regulatory system and may or may not coincide with the actual structure of variable and fixed costs of each generator. Marginal cost pricing regulations have evolved over time (typically a small adjustment every week or so) from relatively simple initial forms to ever more complex algorithms.

Large hydro projects tend to drive the price of power systems because the more hydro energy there is the less thermal generation required. Since hydro tends to be cheaper than thermal generation, more hydro generation will keep system prices lower. This means that, during the dry season prices are likely to be higher because there is more thermal generation, while during the wet season system prices are likely to be lower.

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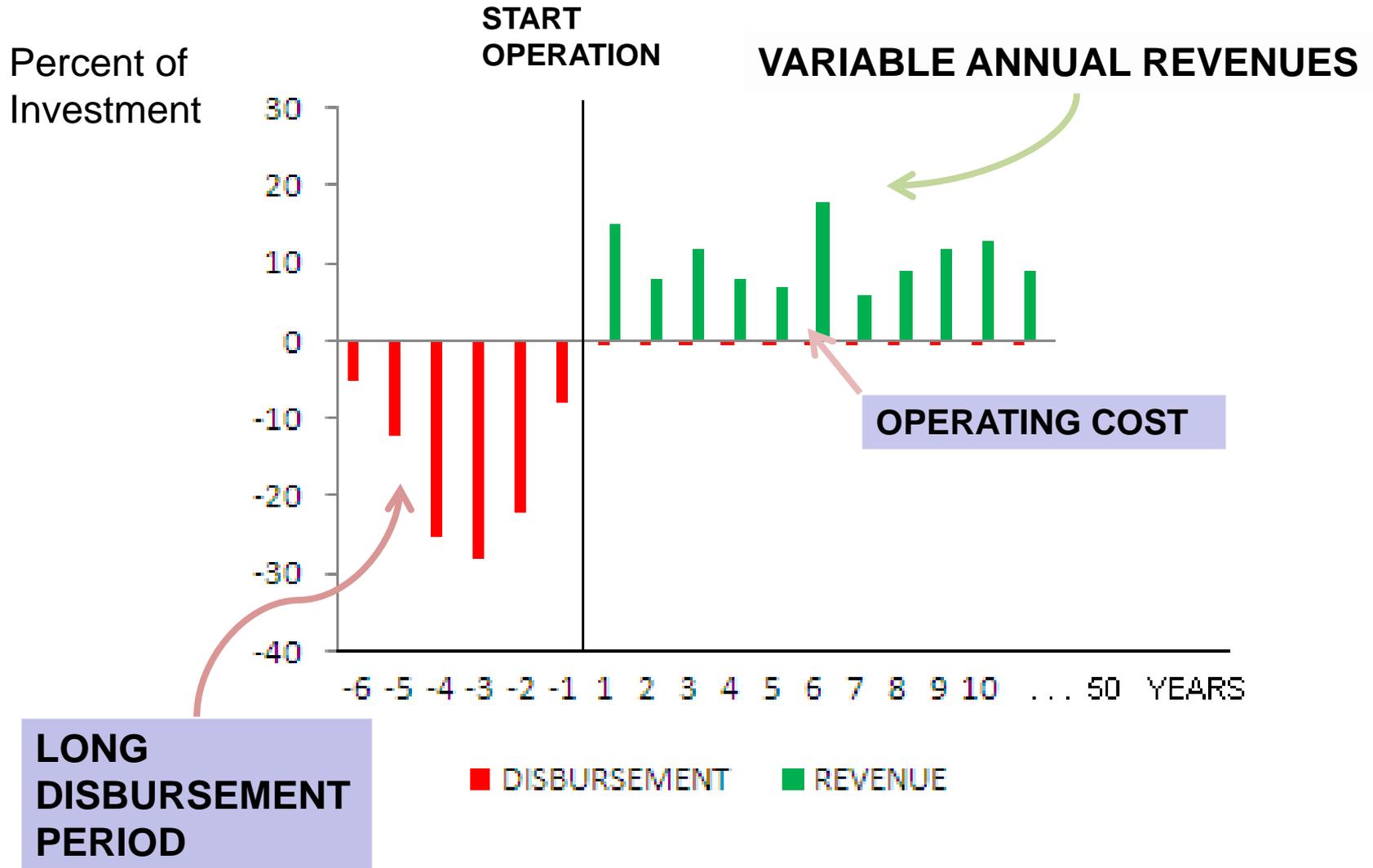
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- Australia: [www.aer.gov.au](http://www.aer.gov.au)
- Brazil: [www.aneel.gov.br](http://www.aneel.gov.br)
- Canada: [www.powerauthority.on.ca](http://www.powerauthority.on.ca)
- Chile: [www.cne.cl](http://www.cne.cl)
- Italy: [www.autorita.energia.it/inglese](http://www.autorita.energia.it/inglese)
- New Zealand: [www.med.govt.nz/](http://www.med.govt.nz/)
- Peru: [www.coes.org.pe](http://www.coes.org.pe)
- UK: [www.ofgem.gov.uk](http://www.ofgem.gov.uk)



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# INVESTMENT BARRIERS: VARIABLE SALES



# Slide 21

## Investment Barriers: Variable Sales

All generation projects require considerable investment that is amortized over part of the life of the project in the form of its annual capital cost. This cost includes return on equity and debt service and is a fixed annual cost to the project. Generation from thermal plants does not vary seasonally in any significant manner, so these plants can offer a steady revenue stream even though they have much higher operating costs than renewable facilities.

Capital costs of medium to large hydro projects are high (rarely below \$1,500/kW), and the construction periods are long (3-10 years, especially for projects with large storage dams). While hydro operating costs are very low the revenue is highly variable because of the seasonality of river flows, particularly in the case of run-of-river plants. This variability can make it more difficult for hydro projects to secure debt. A power purchase agreement can shield the hydro project from uncertainties in market price, but does not shield it from the variability of sales.

The solution to this problem is found in capacity sales. A pricing system or PPA that offers higher capacity payments is more attractive to hydro even if the energy prices are relatively low because it helps stabilize the revenue stream, and thus facilitates financing.

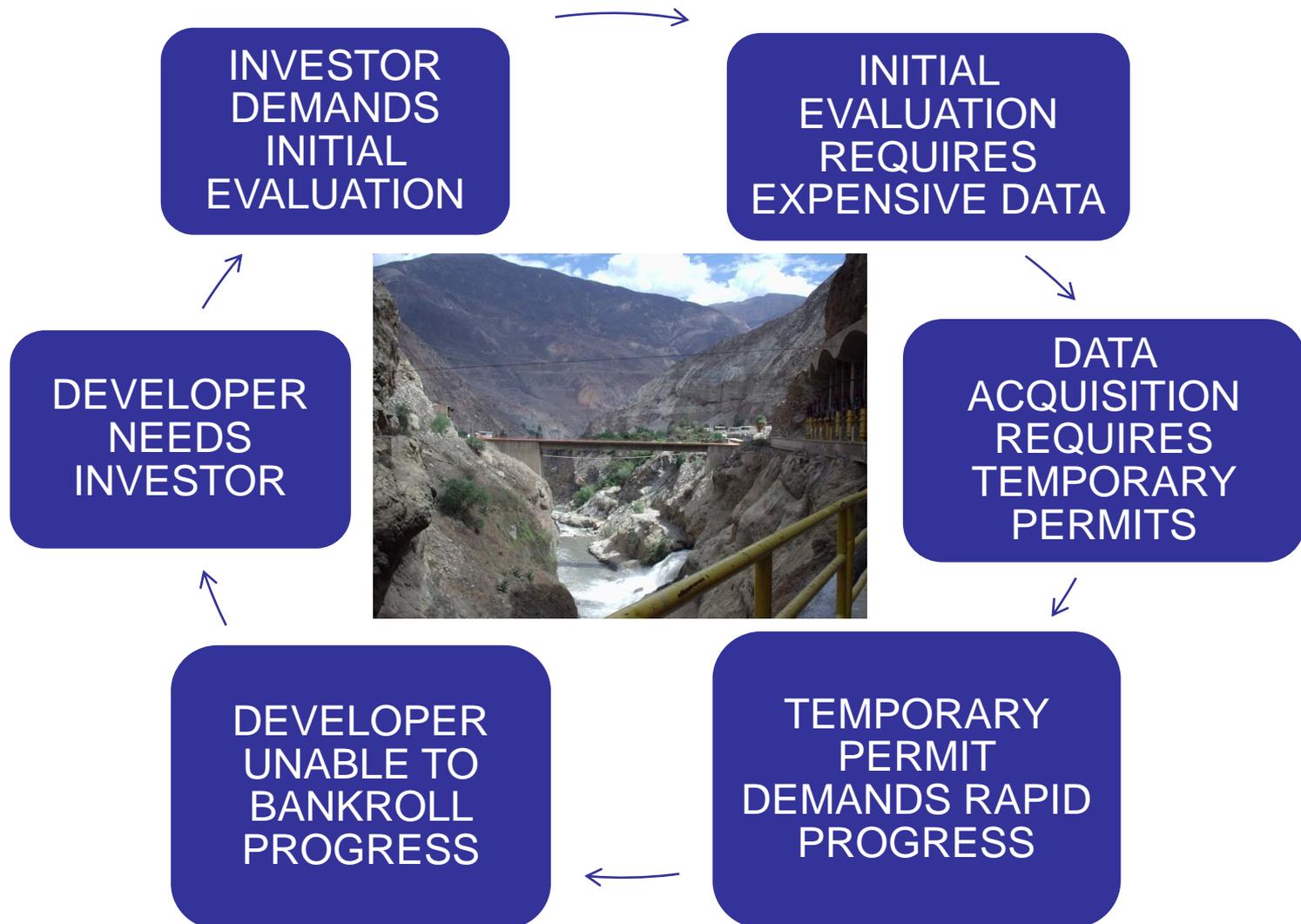
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# INVESTMENT BARRIERS: DATA AND PERMITTING



# Slide 22

## Investment Barriers: Data and Permitting

A hydro plant requires extensive, time-consuming, and costly preliminary studies to establish its feasibility. These studies involve evaluating a site's hydrologic, geologic, and topographic conditions, as well as potential environmental issues involving water rights, water quality, flow regime, fisheries, inundation of lands, and relocation of upstream communities. Thermal plants do not require such extensive site investigations and the process of establishing feasibility, obtaining a license, and securing financing is simpler because there are fewer uncertainties that can delay construction. Some of the scenarios that can delay hydro projects include:

**Developer needs an investor** – Very often a hydro developer does not have enough funds to finance these initial investigations and needs to find an investor. However, to attract an investor it is first necessary to have a temporary license or study permit that allows even very preliminary studies to indicate some expectation of the likely feasibility of the project.

**Data acquisition requires temporary permits** – Temporary licenses usually have very limited duration and are tied to a schedule of completion of different activities so that the site does not become locked in by developers with limited resources. In the United States, the developer is required to provide reports every six months on study progress to the FERC. Unexplained delays may be sufficient cause to revoke study licenses. Thus, a hydro developer must perform a balancing act between the need to advance site investigations with limited funding and the need to have sufficient information to plan the project and seek interested investors. Securing investors willing to finance the initial studies becomes imperative in the race to obtain more permanent licenses and thus secure exclusive rights to the development of a site.

Developers often mitigate these problems by arranging studies and investigations under a success-fee modality so that, in essence, technical support is provided against a share of interest in the development project. In some cases, potential off-takers (users) of energy from the project are asked to sponsor the initial studies against a share of power from the project.

Temporary licenses should be granted with the understanding that developers cannot in every case bankroll all the initial studies. The licensing authority may allow more time, provided the developer can verify an effort has been made to seek interested investors.

Usually licensing a hydroelectric project is an involved process, requiring extensive consultation with regulatory and resources agencies, NGOs, and the public. In Nepal, for instance, it can take approximately 18-24 months to license a small hydro project. Large projects take even longer.

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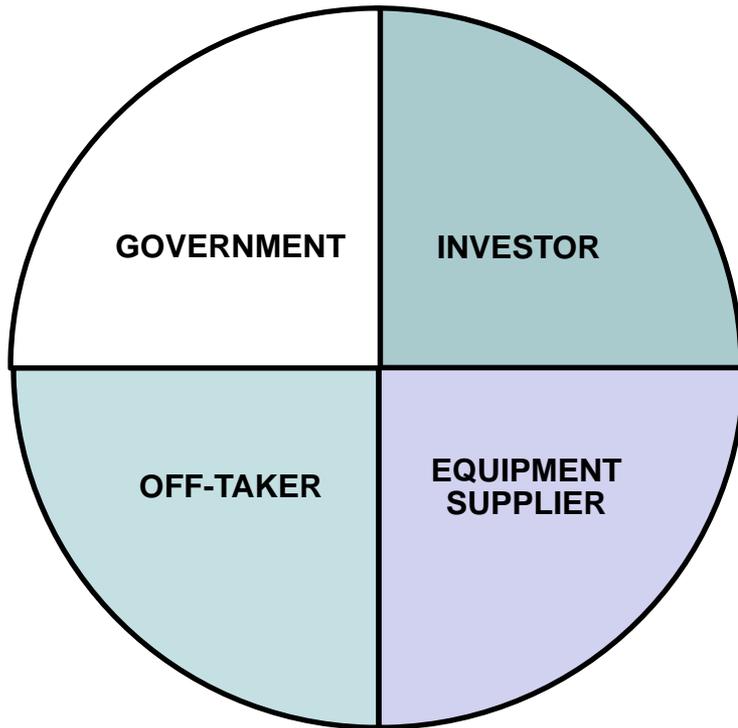
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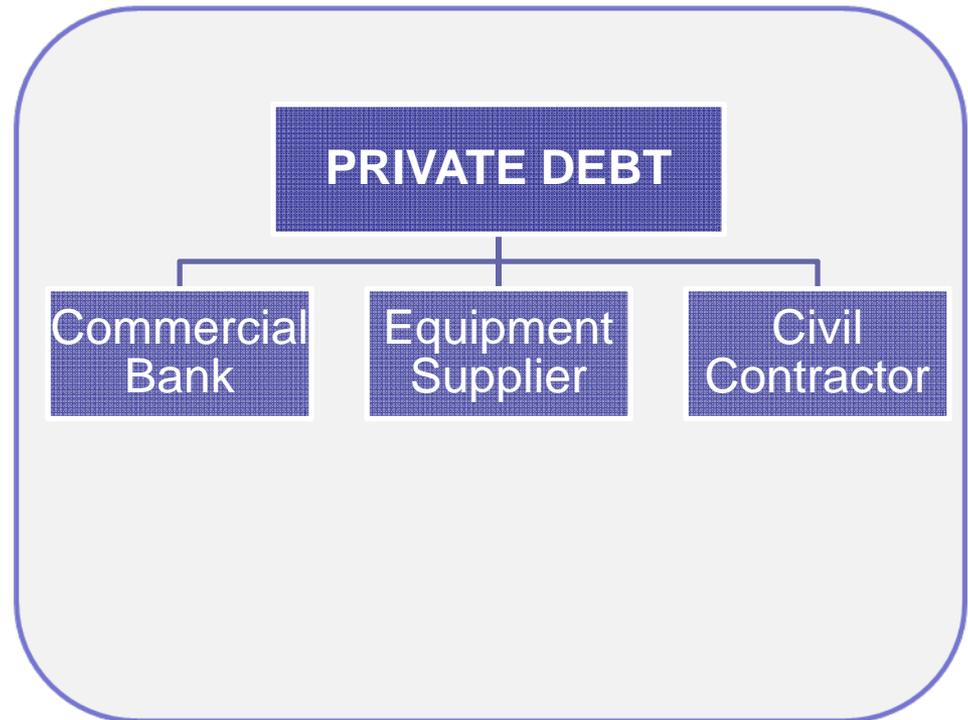
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# CREATIVE PROJECT FINANCE STRUCTURE

## EQUITY



## DEBT



# Slide 23

## Creative Project Finance Structure

### Equity

One way to secure investment in a hydroelectric project is to look for parties that do not expect a return on investment solely from power sales, but also anticipate some other benefits from the development of the project. Equipment suppliers, contractors, and potential energy buyers can all become equity holders and receive some benefit in addition to the direct sales of power.

By integrating off-takers and equipment suppliers into the equity structure, it is possible to raise capital from parties that derive other benefits from the project in addition to receiving a rate of return on their investment. Governments can also contribute equity in the form of land, roads, transmission lines, and other infrastructure necessary to the project. (See also / \* Financing section of the Overview Module)

### Debt

Similarly, creative solutions to debt financing can be sought. A mix of private debt held by commercial banks, debt granted as credit from contractors and equipment suppliers, and debt secured by government through bonds or with development banks under preferential terms can often facilitate financing of large scale developments that cannot be solely undertaken by the private sector. However, such arrangements may require that there be no competitive bidding for equipment procurement or civil contracting, but instead specify negotiations be held for combinations of equipment price and equity offers.

Several developing country governments (e.g., Brazil, Nepal, Kenya, and India) have in the past conducted feasibility studies and environmental assessments of projects prior to requesting multilateral institutions/private sector to fund project development. The governments of Laos and Nepal have obtained loans from multilateral institutions and invested as a partner with the private sector in large hydro developments in their respective countries.

Governments that reformed their laws to let the private sector assume the responsibility to expand generation may not have funding to allocate to preparatory studies and development work. However, private-sector participation is still a relatively new phenomenon, so many projects currently being developed privately have benefitted from groundwork that was laid by the government. In countries that have undertaken electricity reforms, many governments now look to recoup the cost of initial studies from private developers.

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- Best Practices

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## Technical Issues & Solutions



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# TECHNICAL AND ENVIRONMENTAL ISSUES

Hydro projects need careful planning for:

- Large storage reservoirs
- Dam construction and safety
- Grid connection
- River flow management

# Slide 25

## Technical and Environmental Issues

Hydro projects need careful planning to balance technical, social, and environmental impacts:

- These projects tend to occupy a large area and create major modifications to the landscape, especially when they involve large storage reservoirs.
- Transmission lines often extend for hundreds of miles to reach the grid and require extensive corridors across forests, agricultural lands, and urban and semi-urban areas.
- Construction is usually a long process for new projects and involves building access roads; undertaking large earth-moving operations that may involve blasting, tunneling, and digging underground caverns; and diverting river diversions during construction.
- Dams can create barriers to the migration of fish and the movement of sediment and may represent a significant risk to downstream life and property in case of a dam failure.
- Reservoirs may submerge forests and agricultural lands and may require relocation of people and communities.
- The changes to natural river regimes may affect water quality, quantity of water flow, fisheries, and navigation.

On the other hand, hydro projects can also bring extensive benefits beyond the production of low-cost electricity:

- The regulation of river flows can provide irrigation waters for multi-crop harvesting and reliable water supplies to communities.
- Dams provide a means to control floods that annually cause major disruptions in many river basins.
- Dams can help create safe, navigable stretches of river.
- Reservoirs provide opportunities for fishery enhancement and recreation, both in the reservoir and downstream waterways.
- Because of the large investment in their construction, dams offer a significant potential for temporary and permanent jobs in remote communities, while the roads constructed to build the site can bring broader access to goods and markets.
- The availability of stable electricity can encourage new local commercial and industrial activities.

Because of the potential impacts of dams in particular, most countries have developed strict environmental regulations to assist with balancing the economic, environmental, and engineering constraints for proposed hydropower development. Some useful guidelines can be found in USAID regulation 216, which must be followed for all USAID-assisted hydro development.

## References

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- 66. Presentation from Hydro Quebec about its latest development, the Eastmain-Sarcelle Projects
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# RESERVOIRS: POTENTIAL NEGATIVE IMPACTS

- Resettlement
- Loss of land
- Loss of wildlife habitats
- Micro climate change
- Evaporation loss
- Changes to river regime
- Waterborne disease risk
- Carbon emissions from decaying matter

# Slide 26

## Reservoirs: Potential Negative Impacts

Reservoirs are the most controversial part of a hydroelectric power facility, particularly when their creation results in the flooding of large tracts of natural forests or crop lands, or the resettlement of local communities.

Every aspect of a reservoir's potential impact should be addressed during an environmental assessment, allowing time for appropriate mitigation measures to be designed and discussed. Environmental assessment for a project entails quantifying, to the extent possible, the project's benefits, and then balancing these benefits against potential adverse impacts. Careful monitoring during project construction and operations allows for revisions to the project as positive and adverse impacts are realized.

Most countries go through a public involvement process to approve, modify, or reject the environmental assessment. An extreme example of the controversy over reservoirs is the James Bay Project in northern Quebec, Canada. The project covers a series of hydroelectric developments in northwestern Quebec and is one of the largest hydroelectric systems in the world, with a current installed generating capacity of 16,000 MW. The project started in 1972, and the second phase stalled in the 1990s in the face of strong opposition for its many environmental and social impacts, most notably from the indigenous people of Quebec. Eventually, the indigenous tribes reached agreement with the Government of Quebec regarding management of hydro, mining, and forestry resources, allowing the project to move forward.

A key requirement of the environmental assessment is to identify and evaluate realistic alternatives for the project, as well as alternative project details. The alternative designs may include assessment of several cascading projects instead of one high dam, in order to reduce the size of the flooded area and the need to relocate communities; alternative locations for dams and other structures to minimize disruption of sensitive species and cultural resources; alternative routes for access roads to minimize large earthwork and to connect several communities; and alternative operation of the reservoir. Most environmental regulations require the developer to plan, design, and operate the project in order to avoid, minimize, mitigate, or compensate (in that order) for potential adverse effects.

**Photo credit:** NREL

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# RESERVOIRS: POTENTIAL POSITIVE IMPACTS

- Irrigation
- Municipal water supply
- Recreation & tourism
- Fishery development
- Flood control
- Navigation



# Slide 27

## Reservoirs: Potential Positive Impacts

Reservoirs very often serve many purposes in addition to supplying water for power generation. Indeed, several hydroelectric projects were built to take advantage of reservoirs developed for irrigation or other purposes.

In Mexico, for example, three hydro plants (Trojes, Chilatan, and El Gallo, totaling 52 MW of installed capacity) were built on existing irrigation and water supply reservoirs owned by the National Water Commission (CAN) of Mexico. Inelec, a leading independent power producer in Mexico, developed these plants under an agreement that power production was entirely subjected to CNA water releases in accordance with irrigation demands.

Other important uses of reservoirs worldwide include flood control. The Three Gorges Project in China, one of the world's largest and more controversial hydroelectric projects, initially was postulated as a flood control project to mitigate periodic flooding of the Yangtze River.

In some areas with scarce water resources, reservoirs are key to integrated water resource management, providing both irrigation and the electricity to power irrigation pumps. In central Asia, the water of the Syr Darya River and its tributaries is essential for the irrigation of vast areas of Uzbekistan and Kazakhstan. The water is stored in several reservoirs in various countries. The largest reservoir, Toktogul, is located in Kyrgyzstan and also is used for hydroelectric power along a cascade of power plants totaling nearly 2,000 MW. The operation of these reservoirs, formerly planned and controlled by the Soviet Union, is currently subject to complex negotiation among the riparian countries. USAID has provided assistance in developing tools and procedures for integrated water and power use.

In other regions with scarce water resources or very large seasonal variations in precipitation, reservoirs also offer a considerable enhancement to living conditions. The most basic improvement is in water supply and sanitation. In most cases, local communities rely on reservoirs for the supply of abundant and clean water during the dry season. Many communities use reservoirs as a source for small fishing industries and in some interesting cases there is cooperation between power companies and local communities for use of fertile sediment that accumulates in reservoirs.

In Bolivia, for example, the Corani-Santa Isabel hydroelectric complex is the country's largest power producer. The reservoir area is not very large but it is subject to large seasonal variations. The local community has found that the areas uncovered when the reservoir is at low levels are highly fertile and the duration of this low level period is sufficient to grow and harvest agricultural produce. Also, the local municipality finds that the coarser sediment deposited at the tip of the reservoir makes excellent concrete aggregate useful for building local facilities. The power company has agreed to allow farming in the reservoir and removal of coarse deposits during these low level periods, leading to a constructive and mutually beneficial relationship with the local community.

## References

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## Further Reading

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- [www.amazon.com](http://www.amazon.com)



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# DAM FAILURE RISK

Oct  
2002



Sept  
2006



Bar-lin Dam,  
Dahan River,  
Taiwan

Sept 2007

Photo credits:  
Professor Matt Kondolf  
University of California,  
Berkeley

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## Dam Failure Risk

Dams can have a range of serious impacts on the surrounding environment and community. One of the most serious impacts is the potential for dam collapse. Others include the barrier effect on fish migration, sediment transport, and obstacles to navigation.

## Dam Safety

If improperly designed to accommodate extreme hydrologic events, a hydro project has the potential to cause catastrophic flooding. This issue is particularly relevant in light of climate change, which is changing the frequency of meteorological events.

Until the late 1970s, hydrologists utilized techniques to forecast weather events based on probability functions specially designed to fit historical data on extreme events. The probability function was fitted to a historical series (typically 20 to 60 years), based on actual data, and then the magnitude of events with much lower probabilities (1 in 1,000 years or 1 in 10,000 years) could be estimated and used in dam design. At some point hydrologists started to observe that fairly rare events (such as a 1 in 100 year flood) were taking place with disturbingly higher frequency than that predicted by probability functions based on historical samples. This was caused by what we now recognize as climate change.

To adjust to the new reality of increasingly severe meteorological events, hydrologists devised a method known as Probable Maximum Flood (PMF). PMF methodology looks at any possible change in weather conditions and essentially creates the “perfect storm” for any given location. This analysis is then extended throughout the river basin to produce the worst possible flood at the dam site under consideration, so that the structure can be designed to withstand it.

Large civil engineering undertakings like dams and bridges are not usually subject to standardized designs. They require adherence to “sound engineering practice,” which is a more subjective requirement, but usually far more demanding than codes. Engineering practice defines the margin of safety to be used and engineers must make sure that such margins are met under all foreseeable load conditions. PMF is used when the conditions (a combination of dam size, volume of impoundment and risk to life and property) dictate that it must be used, but the ultimate decision is still somewhat subjective and will depend upon the norms in a given country. Governments and insurers rarely get involved because they lack the technical capability, but they may occasionally ask for independent peer review. In the United States FERC does review designs as part of the licensing process, but normally the acceptance of large civil engineering designs relies heavily on the reputation of the engineering firms. Many dam designs undertaken in developing countries may not fall within safety margins considered prudent in the Western hemisphere, where engineering standards are more conservative and large engineering works are closely monitored by various organizations (professional associations, NGOs, and others).

These two examples help illustrate the impact of a real-life dam failure, as well as a best-case scenario:

**Lookout Shoals, NC** – An event that could have been anticipated by PMF analysis (had the concept existed then) occurred in the North Carolina during the summer of 1916. From July 8-10, 1916, remnants of a large hurricane passed directly along the crest of the Blue Ridge Mountains, causing substantial flooding in the Catawba River basin. On July 13, another large hurricane headed toward the Catawba Valley, where the storm system stalled, releasing 22 inches of rain on

July 17, a US record that stood for years. The result was high water on the Catawba nearly 50 feet above flood level and massive infrastructure damage throughout the region. The Lookout Shoals and powerhouse in North Carolina were completely destroyed. Such a combination of events is very rare and therefore it is unlikely that it could be anticipated by a statistical analysis of historical flow records. However, such extreme events, however improbable, can be calculated by knowing the limits of meteorological parameters at the site.

**El Cajon, Honduras** – A better outcome resulted after Hurricane Mitch, one of the most powerful storms ever recorded, stalled over Honduras in 1998, causing destruction to much of the country's infrastructure. The country's largest hydroelectric project, El Cajon, was designed to tolerate a PMF event, and withstood the storm

## Mitigating Factors

Dam safety is taken seriously in most countries at the design and construction stage. However, long-term monitoring and regular inspection of dams are less common. Nevertheless, spectacular failures of dam are few and far between.

FERC and state authorities in the United States require active monitoring, and regular inspection (annual and detailed 5-year inspections) of dams. FERC maintains a list of qualified dam inspectors.

The safety of dams must be evaluated periodically, using several steps.

- The physical integrity of the dam and the site relevant to floods must be evaluated by monitoring seepage through the dam, the stability of slopes in both dam and reservoir, and by ensuring that the downstream flood path is clear of overgrowth and sediment deposits.
- The use of land downstream must be reassessed on a regular basis to monitor developments that could determine a change in risk and, therefore, a change in the criteria that should be used to establish the project flood safety parameters.
- Once the updated criteria are established, the project flood design calculations must be repeated to ensure that the dam meets safety standards in light of new hydrologic events that could have taken place since its commissioning. This may indicate the need to increase spillway capacity or modify operating rules to keep the reservoir lower during the flood season.
- Dam safety can also be improved considerably by remote sensing so that operators can anticipate the arrival of floods and lower the reservoir levels via controlled water releases and reduce the level of peak flows.

## Barrier Effects of Dams

Another serious impact of dams is called "barrier effect," which refers to the disruption of sediment movement, fish migration, and navigation across the site of the dam. Barrier effects on fish migration can be mitigated by fish passages and fish ladders, but their effectiveness depends on the individual fish species. The Bonneville Power Administration in the US Northwest is known for its extensive facilities to maintain and monitor salmon migration across its dams. Barrier effects on sediment can be mitigated by extensive bottom sluices and bottom outlets located in the portions of the river cross sections with the highest density of sediment.

Careful analysis of potential barrier effects is important in the early stages of project planning. In Southeast Asia, the Mekong River Commission, composed of representatives from Thailand, Laos, Vietnam, and Cambodia, is conducting very detailed and thorough studies of the effect of future dams that are being planned across the mainstream Mekong. These studies are expected to result in recommendations that will guide hydropower and other water resources developments

towards an integrated water resource management process that balances benefits against negative impacts and provides for sharing of the burden of mitigating measures.

## **References**

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# IMPACTS OF HYDRO OPERATION



PEAKING OPERATION CAN RESULT IN RAPID AND DANGEROUS FLOW INCREASE

# Slide 29

## Impacts of Hydro Operation

Hydroelectric plants can operate in different ways. Run-of-river projects operate without modifying the river regime and simply use the water when it arrives. Storage projects modify the river regime on a daily or seasonal basis over the lifetime of the project, depending on the amount of storage available to regulate river flows.

It is generally assumed that only plants with large reservoirs modify the river regime by storing water during the wet season and releasing it during the dry season. However, even plants with very modest storage may cause significant river regime modification if they operate as “peaking plants,” which means that they will store water during certain hours of the day to release it during a few hours of peak demand.

The rapid increase in flow resulting from such operation can be detrimental to the river downstream, causing increased bank erosion and disruption of fish and wildlife. It may also affect irrigation intakes. In a worst-case scenario, flow fluctuations can potentially be life threatening if downstream river users are caught by surprise when water is released.

An extreme requirement for a plant expected to operate in peaking mode may be to include a re-regulation reservoir downstream of the plant so that the flows during peak hours can be stored and released in a safe manner. This alternative adds expense, however, and hydro operators can take other precautions to prevent danger to surrounding communities. At most US sites, peaking operations are posted clearly, with warning signs regarding rapid changes in river flows and water levels along the banks downstream of the peaking power plant. Use of loud sirens to alert people to the change in power plant operation has also been very successful in mitigating the dangers of sudden water level changes.

## References

- 117. Optimal Hydropower Operation with Environmental Requirements



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# PRESENTATION

- Technology Overview
- Global Status
- Hydro Economics
- Technical Issues & Solutions
- **Best Practices**

# Slide 30

## Best Practices



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# BEST PRACTICES: NATIONAL WATER RESOURCES DEVELOPMENT POLICY

- Clear government guidelines on water resources and priorities
- Transparent and enforceable regulations to implement national policy objectives
- Independent/autonomous entities:
  - to plan resource development
  - to regulate resource development and operation
  - to assist developers in efficient implementation and compliance
  - To facilitate improvement and address changes in national, developer, consumer requirements/interests

# Slide 31

## Best Practices: National Water Resources Development Policy

In most countries, rivers are considered state assets. Water resources management and development usually falls under the purview of a cabinet ministry. Most governments prioritize the use of water, with the highest priority assigned to municipal water supply, usually followed by irrigation, hydropower, and other water uses. The ministry in charge generally will have divisions assigned to develop municipal supplies, irrigation, hydro power, and other water use projects. Often, these divisions compete for development of individual projects rather than take a holistic look at optimal development of the country's resources.

In many countries, irrigation projects are handled almost exclusively by government departments, while municipal water supply is a local responsibility. In several countries, hydropower development is carried out by a government-owned national electric utility under the cabinet ministry. Thus, technically, the ministry acts as the custodian, developer, regulator, and adjudicator of conflicts in resource development and use, which can result in under-use or misuse of the resource, encourage inefficient or corrupt practices, and compromise development goals and timely delivery of services to the consumer at sustainable prices.

In a best-practices approach, there should be separation of policy, planning, regulatory, and developmental activities for focused, cost-effective projects that achieve national goals and priorities while meeting water use demands within a framework that is environmentally and socially acceptable.

Ideally, the responsible ministry should restrict its role to defining national objectives and policies to develop the resource and prepare laws, regulations, and procedures to meet national objectives. Such regulations ideally would provide incentives for local and international private investment and provide assurances for repatriation of valid equity returns and against nationalization of private investment without due process and equitable compensation. National government and parliamentary authorities should facilitate the following:

- Establishment of independent national planning bodies (national, regional, and sector planning commissions; and river basin authorities) to identify demand for the resource and develop meaningful plans and timeframes for orderly project development. These entities would obtain the ministry's approval for implementation, and advise the ministry to make legislative changes as necessary to address changing sector demands.
- Establishment of a regulatory entity (or entities) to regulate water and power sectors individually or collectively, and formulate and implement regulatory norms and procedures to develop new projects, upgrade existing projects, and decommission outdated projects. The goal is to establish procedures to identify, address, and balance project developments to provide quality service to industrial, commercial, and residential customers at sustainable prices while meeting the needs of investors/developers and resource/environmental agencies.
- Creation of a "one-stop shop" mechanism/authority to assist developers in working through laws, regulations, and procedures to develop and implement projects in a meaningful time frame. Tasks would include assistance to: successfully address inter-ministerial responsibilities such as land acquisition for project construction and acquisition of water rights; prepare project compliance documents regarding environmental and social impact assessments; obtain project permits and licenses; and help developers understand financial, economic, and tax issues.



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# BEST PRACTICES: NATIONAL REGULATORY AUTHORITIES

## Licensing

- Provide clear path to permits/licenses
- Authority and resources to balance project impacts

## Pricing

- Price mechanism for optimal generation mix
- Provide fair capacity value for hydro
- Allow options for recovering fixed costs
- Establish export rules



# Slide 32

## Best Practices: National Regulatory Authorities

Electricity and regulations should provide a clear path for permitting and licensing a project. National electricity regulatory authorities should understand that a firm commitment to a hydropower project requires extensive and often lengthy preparatory studies, and that project developers need authorization to obtain data and conduct preliminary surveys.

A country's national electricity regulatory agency should have the sole authority to provide permits for preliminary studies, licensing of construction, and operation of the project –and for eventual dismantling of the project, where necessary. The regulatory agency should also have the authority to revoke existing permits and licenses for repeated non-compliance with permit/license conditions by the developers/investors.

The regulatory agency should have the authority and resources to create a mechanism for project developers and relevant government agencies to design environmentally, socially, and economically balanced projects. A country's regulatory agency also needs the authority to arbitrate among interested parties to approve power development projects once the project's ability to meet long-term electrical system needs has been established.

For projects with potential cross-border impacts, the national regulatory agencies should integrate river basin organizations as a consultative party in the licensing process since these agencies are in the best position to evaluate basin-wide impacts and issue recommendations on ecological flows, dam safety criteria, fish migration, and other issues of relevance to the entire river basin.

## Pricing

National regulatory authorities play an important role in electricity pricing. In countries where hydro resources are the predominant or only available local energy resource, the regulatory agency should define the procedures to provide appropriate price incentives for development of local resources consistent with national policy. The regulatory agency should be careful not to over-extend the authority to develop local resources at any cost. Tariffs should include incentives for time-of-the-day and seasonal tariff structures to make the best use of available hydropower resources.

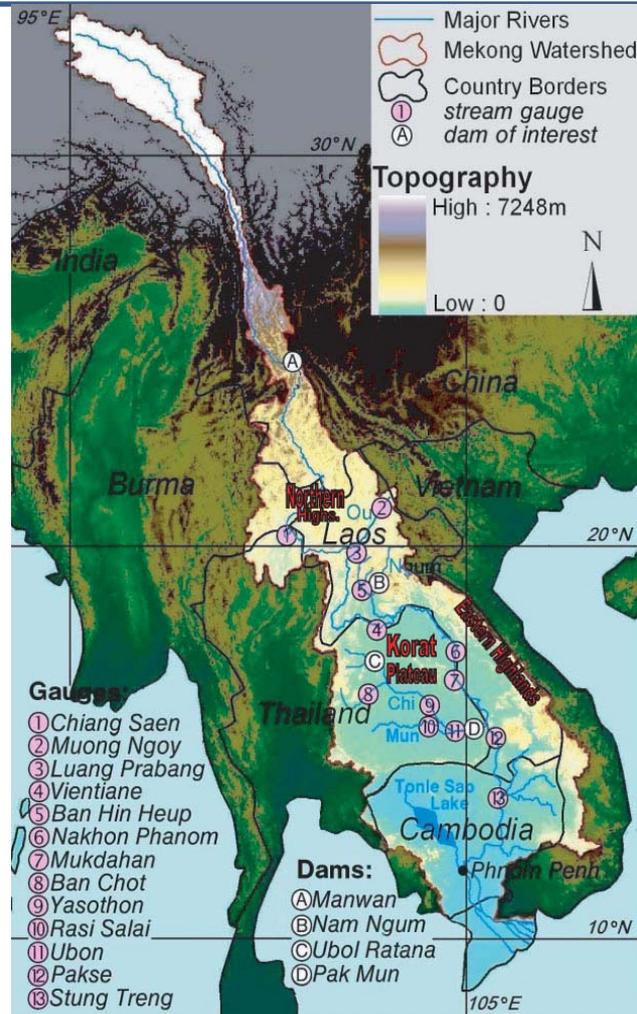
To attract investors to develop local hydro resources, the national regulatory agency may establish pricing rules for merchant plants that recognize the high proportion of fixed costs and offer options for alternative pricing structures such as higher capacity charge, graduated payment structure, and longer licensing periods, consistent with national policies. This may represent a departure from strict marginal cost pricing theory but it recognizes the inherent risk of pricing regime for high fixed cost technologies. Such modified pricing regimes are likely to be more effective than strict marginal cost to drive investments towards the optimum generation mix.

If hydropower exports are a national goal, clear and stable rules must be set to allow fair negotiation with foreign off-takers and preserve any necessary priorities for domestic supply. In all cases, the regulatory entity should ensure that a fair value is allocated to hydropower capacity based on clear rules for determination of dependable capacity and the hydropower facility's contribution to maintaining frequency control in the system.



## Planning & research

- Evaluate basin-wide impacts
- Research critical risks
- Analyze development scenarios



## Policy support

- Promote sustainable development
- Define trans-boundary risks
- Monitor cumulative impacts

# Slide 33

## Planning and Research

River basin organizations have emerged throughout the world to tackle water management issues that cross national boundaries. To be effective, river basin organizations should

- Include all member countries to the extent possible to set out baseline needs, resources inventory, responsibilities, and timelines for development;
- Develop tools and approaches for the comprehensive evaluation of basin-wide social and environmental impacts and to develop workable mitigation measures in consultation with basin member countries;
- Disseminate these tools and the results of studies to basin member countries and hold seminars to educate national regulators on basin-wide impacts;
- Collect and organize data and conduct research on critical risks such as dam failure or the effect of reservoir fill-up on downstream water users; and
- Analyze development scenarios, establish baseline conditions and define balanced limits to hydropower development and define hydropower characteristics that result in the most rapid accumulation of positive impacts.

## Policy Support

River basin organizations should

- Promote national hydropower policies aligned with sustainable river basin development objectives and monitor that such policies are followed;
- Disseminate studies and research on critical trans-boundary risks and promote arrangements for fair compensation and/or cost sharing of mitigating measures; and
- Seek early information on hydropower development to monitor potential cumulative impacts.

## References

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# BEST PRACTICES: HYDROPOWER DEVELOPERS

## Initial Stages

- Evaluate market and regulations
- Anticipate catchment changes
- Consult local water users
- Conduct critical subsurface investigations early

## Advanced Stages

- Integrate project structure
- Request flexible contractor offers
- Involve local community
- Consult regulator and off-taker/dispatch entities
- Train operators and local authorities on safety procedures

# Slide 34

## Best Practices: Hydropower Developers

### Initial Stages

- Developers must evaluate the legislative, regulatory, and environmental requirements, along with demand forecasts and the need for the project, market structure, and price drivers to make a realistic assessment of preliminary project performance outlook.
- There should be a meaningful timeframe for the project, with accurate forecasts of projected demand and the need for the project.
- They should conduct a thorough and critical analysis of the potential for hydro generation, taking account of historic and projected natural or manmade changes to the water resource through land use, diversions, other existing and licensed hydropower development, and climate change effects.
- They should consult with state and local authorities, project-affected communities, and downstream water users to understand their rights and concerns, their tolerance to changes in flow regime, and the potential benefits that they may derive from the project.
- They should conduct early subsurface investigations in critical locations prior to defining project features and preliminary costs.

### Advanced Stages

- Project developers should seek the integration of local system operators/utilities, off-takers, and suppliers, and local financing agencies into the project structure to facilitate financing and limit cost and revenue uncertainties.
- They should prepare a risk-management plan that allocates clearly identified risks and their potential effect on project financing, construction costs, and implementation schedule, to the party (parties) best capable of managing the risk. For example, they may consider preparing tender documents that allow engineering contractors latitude in the scope of work to seek the optimum balance between price and risk sharing between engineering contractor and project owner.
- They should seek extensive involvement of local communities into the project development stage to address social and environmental impacts, and listen to their views of local benefits and risks from the project.

Project developers should keep regulatory and power off-takers/central dispatch authorities fully informed of the project's progress and seek their support to address key issues with development, production, and revenue analysis. This becomes particularly important in the case of sophisticated market-driven systems where revenue will be determined largely by regulatory decisions.

### Project Construction Stages

- Developers should seek to employ as many locals as is possible in the construction and operation efforts to maintain positive community involvement in the project and design actions to train locals for appropriate jobs in the project.
- Developers need to continually work with local communities to maintain a good-neighbor relationship and to identify and resolve potential issues as they arise during the course of the project.

## Operational Stages

Project developers should set in place a mechanism to monitor project activities to ensure compliance with all license requirements in terms of generation and dispatch, as well as environmental and social mitigation measures.

- Operators should plan for daily visual inspection of all water control and water conveyance facilities within practical direct or remote camera access to anticipate problems that could result in expensive repairs or endanger local communities or property.
- They should train and drill project personnel on emergency safety procedures in case of equipment or structural failures that could put at risk project personnel and local communities.
- They should conduct meetings and presentations with authorities at local communities to inform them of safety procedures and coordinate emergency procedures.
- They should monitor downstream developments that could be impacted by changes in river regime.
- They should cooperate in the safe use of project facilities for local and regional development such as shared access roads, access to and use of reservoir water for tourism, recreational or fisheries activities in the reservoir, and in the tail waters of the project.
- As part of local community involvement, developers may consider the opportunity to offer payments to upstream communities provide watershed management services.

It is essential that appropriate measures are carried out to manage and maintain watersheds, river channels, and intake canals to minimize effects on natural hydrology and sedimentation at hydro plant sites. Utilizing upstream communities to manage and enhance watersheds with tree planting, planned tree harvesting, and building and maintaining dams and slopes can help minimize trash and sediment at the hydro plant. In some cases, upstream communities receive payment for such services from the hydro operator, thereby creating a win-win situation with local job opportunities and cost-effective and environmentally friendly maintenance of watersheds.

## References

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