# DAMS FOR HYDROELECTRIC ENERGY

**Committee on Dams for hydroelectric Energy**

**International Commission on Large Dams (ICOLD)**

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## SYNOPSIS

The Bulletin is intended as a general document aimed at a wide technical audience involved with or affected by hydropower. It offers an overview of the main topics related to hydropower and makes particular reference to dams as part of hydropower developments.

Basic background data are presented for electricity demand and production with specific reference to hydro-electricity production. Some statistics are presented for hydropower dams, hydropower plants, conventional and pumped storage, currently in operation or under construction.

Key aspects of hydropower production are discussed, highlighting various ancillary services that hydropower can provide. Data are presented about typical capital and both internal and external operating costs. Environmental and social impacts are discussed and specific reference is made to the impact reservoirs have on greenhouse gas emissions.

The current extent of hydropower development is discussed, both in countries where the hydropower potential has been extensively developed and in those where very large potential still exists. The influence on hydropower of national and international policies aimed to favour the development of renewable energies is also briefly discussed.

Considering the recent increased attention, a section is dedicated to the exploitation of tidal energy by means of barrage systems.

Reference sources of information, on hydropower in general and interesting case-histories, are provided at the end of the Bulletin.

Although significant effort and review has been carried out in an attempt to ensure that the presented data is the most current and up to date, it is possible that some data may be dated or unsubstantiated. Regardless it is believed that the intent of the Bulletin and reliance of the information reported therein is not compromised.

# 1. ELECTRICITY DEMAND AND PRODUCTION

As the world's population grows there is an ever increasing demand for potable water, food, natural resources, industry and energy. Over millennia man has used energy provided by animals, water, wind and more recently, gas, fossil fuels and electricity.

Electricity is unique in its ease of distribution and in its multitude of applications. As a result the growth in demand for electricity has been faster than any other end-source of energy. Figure 1 shows a fairly constant growth in world electricity demand of about 3% per annum over a 30 year period from 1970 to 2000.

Growth in electricity demand in the OECD Countries[1] continues at a level close to the historic trend. Emerging countries are however, reporting high rates of economic growth and associated high growth in electricity demand. China has shown the highest levels of growth.

Currently the United States and China are the world's largest electricity producers (about 20% each). Power generation in Asia, excluding China, now exceeds that produced by North America or Europe. Figure 2 shows the current distribution of electricity generation by region.

Historically electricity has been generated by burning fossil fuels or by using hydropower. More recently there has been the development of nuclear power stations and generation using wind power, solar, geothermal and other technologies. The growth in electricity production, by fuel, is shown in Figure 3. From Figure 3 it is clear that more than 60% of the world's electricity production is currently from fossil fuels, primarily coal, oil and natural gas. Figure 4 shows the current world power generation mix by fuel.

Almost invariably electricity generation using fossil fuels is the most economical. Accordingly, developing countries are expected to largely follow a carbon-intensive development path, similar to that taken by industrialised nations in the past. It will require policy changes and considerable investments in new technologies to change this trend. It is unlikely that developing countries will lead the way in this respect.

Various agencies have developed future electricity demand scenarios (see Reference 2). These scenarios indicate that world energy consumption will

[1] Countries belonging to the "*Organisation for Economic Co-operation and Development*": Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

increase by about 30% by year 2020, primarily as a result of rapid growth in demand in China and India.

As a result of this growth, and the expected focus on fossil fuels, it is anticipated that the world $CO_2$ emissions will also increase by about 30%. This direct link between energy use and greenhouse gas emissions calls for more efficient technologies for the supply and use of energy and a transition to cleaner and renewable energy sources.

The International Energy Agency has considered the role of existing and near-commercial renewable energy technologies in possible future scenarios. They developed two possible scenarios for year 2030 as follows:

- "Reference Scenario", in which renewables will constitute about 14% of the world primary energy demand.
- "Alternative Policy Scenario", in which renewables will constitute about 16% of the world primary energy demand. This scenario assumed implementation of various policies currently being considered to ensure energy security and to reduce greenhouse gas emissions.

In addition to the energy needs illustrated above, it is also useful to keep in mind the eight Millennium Development Goals (MDGs) that 189 United Nations member states and many international organizations have agreed to pursue to improve the social-economic conditions in the world's poorest countries and to encompass universally accepted human values and rights:

- Eradicate Extreme Poverty and Hunger
- Achieve Universal Primary Education
- Promote Gender Equality and Empower Women
- Reduce Child Mortality
- Improve Maternal Health
- Combat HIV/AIDS, Malaria, and Other Diseases
- Ensure Environmental Stability
- Develop a Global Partnership for Development

Though access to energy for all is not an MDG in itself, it is evident that it remains crucial for achieving the MDGs.

From the above it is evident that the world needs energy at an ever increasing rate and that much of the energy needs will have to be supplied by generating electricity. It is also clear that man, in his quest for energy, will probably increase greenhouse gas emissions significantly over the next twenty years. Apart from the negative consequences associated with climate change it should also be borne in mind that fossil fuels are not renewable and that resources are finite. Accordingly, there would have to be significant investment in the development of renewable technologies.

Hydropower currently accounts for about 16% of the world's electricity generation as shown in Figure 4. At present it is the biggest source of production from renewable sources. The rest of this report will focus on the role of hydropower only.

## 1.1. HYDROELECTRICITY

While in the OECD Countries the production of hydro-electricity has remained almost constant over the last decade, after a period of almost thirty years of constant growth, in the non-OECD countries the hydro-electric production shows a continual growth, particularly significant in China, Brazil and India.

Hydropower plants currently contribute to electricity generation in some 160 countries. More than half of the national electricity supply is produced from hydro in about 60 countries. Despite this large footprint, more than 50% the world's total hydro production comes from only six countries (China, Brazil, Canada, USA, Russia, Norway) as shown in Figure 5. Some notes on the development in each of the countries follow below:

**China** currently has the largest hydroelectric production capacity in the world (Reference 14, Reference 15). In addition it has the largest hydropower development program in the world. This development program reflects China's commitment to developing its energy production capacity whilst, at the same time, limiting the increase of $CO_2$ emissions. Hydropower installations reached at the end of 2010 about 220 GW, achieving 40% of the technically feasible potential, and accounting for 22% of China's total installed capacity. The annual hydropower generation is about 690 TWh (2010 data), accounting for about 16% of China's total power generation. By 2020 the installed hydropower capacity should reach around 300 GW. Although there are some 50 000 hydropower plants in China only about 20 have an installed capacity of more than 1000MW and more than 45 000 plants have an installed capacity of less than 50 MW.

**Brazil** is currently the second largest hydroelectric energy producer in the world despite the fact that it has a smaller installed capacity than the USA. In 2011 the country produced about 91% of its electric energy demand from hydro. About 82 GW of hydropower are currently installed (2011), accounting for about 70% of the total installed capacity in Brazil (Reference 55). More than 9 GW of hydropower capacity are under construction (60% of which by private developers), and further 32 GW are planned to start operation until 2020. More than 40 new hydropower projects are planned to be commissioned before the end of 2020 (Reference 56) of which the largest are:

- Belo Monte project with a capacity in excess of 11 GW.
- Sao Luis do Tapajós project with a capacity in excess of 6 GW.
- Four other projects each with a planned capacity in excess of 1 GW.

According to the National Energy Plan with a forecast until 2030, the percentage of national energy produced from hydro plants will continue in the 70 to 75%

range (Reference 56). The total hydropower potential of Brazil (developed and undeveloped) is estimated in 260 GW, of which 43% are situated in the Northern region. However, considering economic, social and environmental restriction, the potential will be reduced to 174 GW. The Brazilian Government encourages the construction of small hydropower plants and buys the energy produced. According to Brazilian Law and regulations small hydropower plants are defined as an installation with a capacity up to 30 MW and a reservoir with a maximum surface of 13 $km^2$. Usually they are run-of-the-river plants with a small dam and a low environmental impact. In the decade 2001 to 2010 one hundred seventy eight small hydropower plants entered into operation with a total installed capacity of 2 425 MW (Reference 57). At present (2011) the installed power capacity totals about 3.90 GW.

**Canada** is currently the third largest hydroelectric energy producer in the world. Hydroelectricity is the leading type of power generation by utilities in Canada, with a share close to 60%. Hydro power is the purpose of the great majority (about 70%) of large dams in Canada. It is estimated (Reference 16) that more than 70 GW of hydropower have been already developed in Canada (a very accurate estimate is difficult, as there are currently many projects coming on stream and in the works), for a hydropower generation of about 370 TWh/year. The hydroelectricity is produced from 450 large and medium scale stations and more than 200 small plants (less than 10 MW). The potential for further hydroelectric development in Canada is large. The undeveloped hydropower potential is estimated to be of the order of 160 GW (capacity that can technically be developed, not considering feasibility factors such as economic or social issues). Some 80% of the countries hydro resources are located in the provinces of Quebec, British Columbia, Yukon, Alberta, Ontario and the Northwest Territory.

**The United States of America** is currently the world's fourth largest producer of hydro-electric energy although it has the second largest installed capacity. The relatively low energy production (about 300 TWh/year, accounting for about 7% of the total electricity production, see Reference 41) is as a result of the countries large investment in pumped storage schemes, of the 100 GW installed about 20 GW are pumped storage plants used for the generation of peaking power and for other purposes. Furthermore, some 60% of currently planned expansion will be from pumped storage plants and marine energy (see Reference 42). Few new large hydro plants are planned and much of the future expansion will come from retro-fitting hydro to existing dams and/or refurbishment and modernisation of existing hydropower facilities.

**Russia** is a major hydropower producer (about 165 TWh/year). Hydropower constitutes about 20% of the country's total power demand. The total installed hydropower capacity is about 45 GW, more than 7 GW of hydro capacity are under construction and further 12 GW are planned. Development of hydropower in Russia is made difficult as a result of the remoteness of the bulk hydro resources from the primary power consumers. Accordingly, it is estimated that only about 850 TWh/year would be economically exploitable compared to the hydro potential of about 2900 TWh/year. Five river basins account for most of the developable potential as follows: Yenisei (34%), Lena (27%), Ob (11%), Amur (7%) and the Volga (7%). To date only about 20% of the potential of these rivers is exploited. Spatially, about 40% of the countries hydro capacity is in European Russia, some 23% is in Siberia and less than 6% is in the Far East of the country.

**Norway**. Almost all electricity generation in Norway is by hydro power with only about one percent coming from other sources. The annual hydroelectric production is about 125 TWh. The installed output is 29,50 GW. Despite the heavy reliance on hydro, no new large dams on new projects have been constructed in the last decade. Two major large dams, Stolsvatn dam and Hogganvatn dam have recently been replaced, and there is a major upgrading program underway for Norwegian large dams. In 2012/2013 a new double curvature arch dam 50 m high is under construction at Sarvsfossen. Since 2005 small hydro has received political acceptance and positive public opinion and 30–50 small hydro power plants (<10 MW) are commissioned annually. Increasing energy prices in Norway fully funded this growth without any subsidies until 2011.

The following future trends are noted for Norway:

- Due to the increasing age of the hydropower system, major upgrading programs must come in the near future.
- Development of wind and solar power in conjunctive use with hydro releases some of the large reservoir regulation capacity in Norway, for development of peaking power or pumped storage projects. With sufficient cable connections, it is estimated that some 20 GW or more could be developed in Norway without major environmental issues or development of new reservoirs. There are however some limitations in this process. Cable connections are expensive. Environmentally acceptable reservoir drawdown/filling rates are sometimes restrictive. There is currently a lack of developed business criteria for balancing power.
- Green certificates agreed between Sweden and Norway from 2012 as a part of an EU-agreement will most likely speed up the process with development of small hydro and upgrading of existing power schemes. The agreement will introduce 11% new energy in 2020 compared to 2011.

# 2. DAMS AND HYDROPOWER PLANTS

## 2.1. DAMS

Based on the ICOLD criteria for large dams, principally a structural dam height above foundation not less than 15 metres, it is estimated that there are more than 52 000 large dams in operation around the world. This estimate is derived from data in the 2010 ICOLD World Register of Dams which lists more than 38 000 dams, and takes into account that China has, to date, not yet reported dams between 15 and 30 m high. Estimates put the number of Chinese dams in this range at more than 14 000.

Most dams around the world are built with irrigation as the primary purpose. Hydropower is the second biggest driver for building dams. Dams having hydropower as the primary purpose, or one of the main purposes, are estimated to be in the order of 25% of the total. The percentage of dams built primarily for hydropower purposes vary geographically, ranging between 6-7% in Africa and Asia excluding China, to more than 30% in Europe. Single-purpose hydropower dams are most common in Europe and South America.

As head is of primary concern in generating hydro power, it is no surprise that dams built primarily for hydroelectric power production account for many of the world's highest dams. In fact, hydropower is the primary purpose for more than 80% of all dams higher than 200 m, and the highest dams in the world are all hydropower dams as shown in the Table 1, that follows [2].

| **Dam name** | **Height (m)** | **Type** | **Country** | **Primary Purpose** |
|---|---|---|---|---|
| Nurek | 300 | Embankment (earth) | Tajikistan | Hydroelectric |
| Xiaowan | 292 | Concrete (arch) | China | Hydroelectric |
| Grande Dixence | 285 | Concrete (gravity) | Switzerland | Hydroelectric |
| Inguri | 272 | Concrete (arch) | Georgia | Hydroelectric |
| Manuel Moreno Torres (Chicoasén) | 261 | Embankment (earth) | Mexico | Hydroelectric |

[2] Vajont dam (260 m, Italy) is not reported in the Table because, after the landslide that filled its reservoir in 1963, it's no more used for power production. Even if still included in the register of large Italian dams, it's now acting as a huge "retaining wall".

| | | | | |
|---|---|---|---|---|
| Tehri | 261 | Embankment (earth) | India | Hydroelectric |
| Álvaro Obregón | 260 | Concrete (arch) | Mexico | Irrigation |
| Mauvoisin | 250 | Concrete (arch) | Switzerland | Hydroelectric |
| Alberto Lleras (Guavio) | 243 | Embankment (rock-fill) | Colombia | Hydroelectric |
| Mica | 243 | Embankment (earth) | Canada | Hydroelectric |
| Sayano Shushenskaya | 242 | Concrete (arch-gravity) | Russia | Hydroelectric |

Table 1

Some interesting data for the highest dams in the world, all hydropower dams, are reported hereafter. Pictures of the dams are shown in Figure 6.

– Nurek dam. Currently the highest dam in the world. It is an earthfill dam, with a central core. Construction began in 1961 and was completed in 1980. It is built in a highly active seismic zone and has, since completion, been subjected to many large earthquakes. The hydroelectric power plant has nine generating units, with a total installed capacity of 3 000 MW. The reservoir has a capacity of 10 500 million $m^3$, a surface area of about 100 $km^2$ and a length of more than 70 km. Water is also supplied to irrigate about 700 $km^2$ of farmland.

– Xiaowan Dam is a double curvature arch dam on the Mekong River in Yunnan Province, southwest China. The dam has a crest length of 900 m, and varies in thickness between 13 m at the crest and 69 m at the base. Construction was completed in 2010. It forms a reservoir of 15 000 million $m^3$ capacity. Total installed capacity is 4 200 MW.

– Grande Dixence Dam is currently the world's tallest concrete gravity dam. It creates a reservoir of about 400 million $m^3$, at an altitude in excess of 2000 m a.s.l. Construction was completed in 1964. The dam supplies water to four power stations with a total installed capacity of 2 069 MW, generating about 2000 GWh/year (a fifth of the storable energy produced in Switzerland). The Bieudron power station power station (3x423 MW, 1883 m gross head) was out of service for 9 years following the rupture of the penstock in 2000; the rehabilitation was completed in 2009 and the operation of the plant started again in January 2010.

– Inguri Dam is currently the highest concrete arch dam in the world. Construction began in 1961 and was completed in 1987. The power station has 20 turbines with a total installed capacity of 1 320 MW, generating about 3 800 GWh/year, approximately half of the total electricity supply in Georgia.

- Manuel Moreno Torres (Chicoasén) is a zoned rockfill dam with earth core. It has a crest length of 584 m and creates a reservoir of 1 440 million $m^3$. Construction started in 1975 and was completed in 1980. The power station has eight generation units of 300 MW each.

- Tehri Dam is an embankment dam with a crest length of 575 m. Construction began in 1978 and was completed in 2006. Construction of the dam initiated a vigorous debate about social and environmental concerns. The dam stores some 2 600 million $m^3$ which supplies a power station with an installed capacity of 1 000 MW as well as a 1 000 MW of pumped storage capacity. Water is also supplied for irrigation and municipal water use.

*a) Dams under construction*

More than half (56%) of the major dams (height > 60 m) currently under construction in the world, have hydropower as part of their purpose, and about a third (30%) have hydropower as their sole or main purpose. The statistics are shown in Figure 7, referring to the ICOLD geographical subdivision[3] (source data from Reference 5).

The majority of dams currently under construction for hydropower generation are Rockfill, CFRD or RCC, each making up about 20% of the total.

Many of the dams currently under construction for hydropower are large, particularly in China, as highlighted by the following examples:

- Jinping-1 Dam, a 305 m high concrete arch dam, with a crest length 568 m, will become the highest dam in the world. It will create a reservoir of 7 700

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[3] **Africa**: Algeria, Angola, Benin, Botswana, Burkina Faso, Cameroon, Congo, Côte d'Ivoire, Dem. Rep. of Congo, Egypt, Ethiopia, Gabon, Ghana, Guinea, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritius, Morocco, Mozambique, Namibia, Nigeria, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe;
**Asia**: Afghanistan, Bangladesh, Brunei, Cambodia, China, India, Iran, Iraq, Japan, Jordan, Kazakhstan, Kyrgyzstan, Laos, Latvia, Lebanon, Malaysia, Myanmar, Nepal, North Korea, Pakistan, Philippines, Saudi Arabia, Singapore, South Korea, Sri Lanka, Syria, Taiwan/China, Tajikistan, Thailand, Uzbekistan, Viet Nam;
**Austral-Asia**: Australia, Fiji, Indonesia, New Zealand, and Papua-New Guinea;
**Europe**: Albania, Armenia, Austria, Azerbaijan, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Lithuania, Luxembourg, Macedonia, Moldova, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom, Yugoslavia;
**North America**: Antigua, Canada, Cuba, El Salvador, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Trinidad & Tobago, United States;
**South America**: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Guyana, Panama, Paraguay, Peru, Suriname, Uruguay, and Venezuela

million m$^3$ on the Jinping bend of the Yalong River, and supply a 3 600 MW power plant.

– Xiloudu Dam, a 278 m high concrete double curvature arch dam, with a crest length of 700 m, will create a total storage capacity of about 13 000 million m$^3$ on the Jinsha River (upper tributary of the Yangtze River).

– Nuozhadu Dam, a 261 m high embankment dam, with a crest length of 608 m , on the Mekong River, will create a reservoir of about 1 100 million m$^3$, to support a 5 850 MW power plant.

– Laxiwa Dam, a 250 m high concrete arch dam, with a crest length of 460 m, on the upper Yellow River, will create a reservoir of about 21 700 million m$^3$, to supply a 4 200 MW power plant (the first two generators, 700 MW each, were commissioned in 2009).

Very high hydropower dams under construction in other parts of the world are as follows:

– Kambaratinsk dam will be a 275 m high embankment dam on the Naryn River in central Kyrgyzstan, that will supply a 2 000 MW power plant.

– Deriner dam will be a 249 m high double curvature concrete arch dam with a crest length of 720m. It is on the Coruh River in Turkey. The dam thickness varies from only 1 m at the crest to 60 m at the base. It will form a reservoir of about 2 000 million m$^3$ and supply a 670 MW power plant.

– Gilgel Gibe III dam, a 243 m high roller-compacted concrete dam, on the Omo River in Ethiopia, with an associated 1 870 MW power plant (the largest hydroelectric plant in Africa once completed). It's a part of the Gibe cascade, including the existing Gibe I dam and Gibe II power plant as well as the planned Gibe IV and Gibe V dams.

## 2.2. CONVENTIONAL HYDROPOWER PLANTS

About 900 GW of hydropower are currently installed in the world. The following Table 2 lists the largest hydroelectric plants currently in operation.

| **Dam name** | **Country** | **Year of completion** | **Capacity (MW)** |
|---|---|---|---|
| Three Gorges | China | 2009 | 22 500 |
| Itaipu | Brazil/Paraguay | 1984-2007 | 14 000 |
| Guri | Venezuela | 1986 | 10 200 |
| Tucuruí | Brazil | 1984/2006 | 8 370 |

| | | | |
|---|---|---|---|
| Grand Coulee | USA | 1942/1980 | 6 809 |
| Sayano Shushenskaya | Russia | 1985/1989 | 6 400 |
| Longtan | China | 2009 | 6 300 |
| Krasnoyarskaya | Russia | 1972 | 6 000 |
| Robert-Bourassa | Canada | 1981 | 5 616 |
| Churchill Falls | Canada | 1971 | 5 429 |
| Bratskaya | Russia | 1967 | 4 500 |
| Ust Ilimskaya | Russia | 1980 | 4 320 |
| Xiaowan | China | 2010 | 4 200 |
| Laxiwa | China | 2011 | 4 200 |
| Yaciretá | Argentina/Paraguay | 1998 | 4 050 |
| Tarbela | Pakistan | 1976 | 3 478 |
| Ertan | China | 2000 | 3 300 |
| Pubugou | China | 2011 | 3 300 |
| Ilha Solteira | Brazil | 1969/1974 | 3 444 |
| Xingó | Brazil | 1994/1997 | 3 162 |
| Gezhouba | China | 1988 | 3 115 |
| Nurek | Tajikistan | 1979/1988 | 3 000 |

Table 2

Some additional data for the largest hydropower plants in the world follows.

– **Three Gorges Project** is the world's largest hydroelectric plant in terms of installed power capacity. It harnesses the Yangtze River with a drainage area of 1 million km$^2$ and an average annual runoff of 450 000 million m$^3$. The dam is a concrete gravity dam 181 m high with a crest length of 2 300 m. It creates a reservoir of about 40 000 million m$^3$ of which 22 000 million m$^3$ is reserved for flood control. Construction started in 1993 and spanned 17 years. In addition to power generation, flood control and navigation improvement are two fundamental benefits of the project.

Fifteen million people and 1.5 million hectares of farmland are now protected from floods, decreasing the flood frequency from under 10 years to about 100 years. Some 660 km of navigable waterways have been improved to allow navigation of 10 000 ton fleets between Shanghai and Chongqing. The installed capacity is achieved by 32 units of 700 MW each (and two smaller generators, 50 MW each). The annual generation is about 85 TWh (2010 data). In 2012 the last turbine has been connected to the country's grid.

- **Itaipu** is currently the world's largest plant in terms of annual energy generation, generating more than 90 TWh/year. Its regional importance was emphasized by an interruption that occurred in 2009, when transmission lines were disrupted by a storm, causing massive power outages, blacking out the entire country of Paraguay for 15 minutes and plunging Rio de Janeiro and São Paulo into darkness for more than 2 hours. The dam, 196 metres high and almost 8 km long, is composed by five types of dams: earthfill dams on the wings, a rockfill dam on the left bank, a concrete buttress dam on the right and left banks, a concrete hollow gravity main dam in the riverbed and a concrete gravity dam in the diversion channel. The reservoir covers an area of 1 350 km$^2$ with a storage capacity of 29 000 million m$^3$.

- **Tucuruí** is located in the Brazilian Amazon rainforest, in the State of Pará. Its main purposes are hydroelectricity production and navigation. The main dam in the riverbed is a 95 m high earth-rockfill dam, 6.46 km long. The flip-bucket spillway, equipped with 23 radial gates, has a discharge capacity of 110 000 m$^3$/s. The wall incorporates two navigation locks, each 210 m long and 33 m wide. The reservoir has a total capacity of 50 000 million m$^3$. The hydropower station houses 25 generation units to produce 40 TWh/year with an installed capacity of 8 370 MW.

- **Guri** is located in Bolívar State, in Venezuela. The dam is a composite dam comprising a concrete gravity section and embankment section. The wall is 162 m high and 7.4 km long. The dam was constructed in two stages. Stage one was constructed from 1963 to 1978 with a maximum wall height of 106 m. The second construction stage, concluded in 1986, raised the wall to its final height. An on-going refurbishment project, started in year 2000, will extend the operating life of the power plant by 30 years. The annual generation is more than 50 TWh. The reservoir has a capacity of about 138 000 million m$^3$, reserved for flood attenuation purposes.

- **Grand Coulee** is located in the state of Washington, USA. Its main purposes are hydroelectricity production and irrigation. Constructed between 1933 and 1942, originally with 2 power plants. Grand Coulee Dam today supplies 4 power houses comprising 33 hydroelectric generators. It is the largest power plant in the USA. The annual generation is about 25 TWh. The dam is a gravity dam 168 m high and 1 592 m long. The reservoir capacity is about 12 000 million $m^3$. As the centre-piece of the Columbia Basin Project, the reservoir supplies water for the irrigation of 2 700 $km^2$.

*a) Hydropower plants under construction*

Over 150 GW of hydropower are currently under construction in the world, most of them in Asia. Some very large schemes currently under construction are listed in the next Table 3.

| Dam | Country | Capacity (MW) | Construction start | Scheduled completion |
|---|---|---|---|---|
| Xiluodu | China | 13 860 | 2005 | 2017 |
| Belo Monte | Brazil | 11 233 | 2011 | 2015 |
| Xiangjiaba | China | 6 400 | 2006 | 2015 |
| Nuozhadu | China | 5 850 | 2006 | 2017 |
| Jinping 2 | China | 4 800 | 2007 | 2014 |
| Jirau | Brazil | 3 750 | 2009 | 2015 |
| Jinping 1 | China | 3 600 | 2005 | 2014 |
| S. Antônio | Brazil | 3 150 | 2008 | 2015 |
| Boguchanskaya | Russia | 3 000 | 1980 | 2013 |

Table 3

The data in the Table shows the major role played by China and Brazil. Most of the largest hydropower plants currently under construction are in China.

The Xiloudu plant, the largest hydropower plant currently under construction in the world, will control runoff from the Jinsha River which has a drainage area of 0.45 million $km^2$. The dam will have many ancillary benefits including sediment retention, flood control, improved navigation and some ecological improvements.

## 2.3. PUMPED STORAGE POWER PLANTS

Pumped-storage plants, serve to supply peaks in electricity demand (see paragraph 3.1), by releasing energy accumulated during off-peak periods.

Although they are net consumers of energy they allow accumulation of cheap energy, at times of surplus, for release at times of peak demand when energy is expensive. Such use is cost effective in systems with considerable inflexible generation capability such as nuclear and thermal. Pumped storage is also useful to regulate energy supply from renewable sources that do not necessarily generate power when it is needed, such as wind and solar plants. They have some distinctive technical features when compared with conventional hydropower plants including:

– greater power output from comparatively smaller reservoirs;
– no need of natural inflow to the reservoirs;
– considerably fewer hydrological and topographical restrictions;
– comparatively less impact on the surrounding ecosystems.

The following Table 4 lists some of the largest pumped-storage plants currently in operation.

| **Plant** | **Country** | **Capacity (MW)** |
|---|---|---|
| Bath County | USA | 3 000 |
| Guangzhou (or Guangdong) | China | 2 400 |
| Huizhou | China | 2 400 |
| Okutataragi | Japan | 1 932 |
| Ludington | USA | 1 872 |
| Tianhuangping | China | 1 836 |

Table 4

Some very large pumped-storage plants currently under construction include the following (Table 5):

| | | |
|---|---|---|
| Kannagawa | Japan | 2 820 |
| Dniester | Ukraine | 2 268 |
| Ingula | South Africa | 1 332 |

Table 5

Most pumped-storage plants currently in operation use synchronous generator-motors with constant operating speed, both in generating and pumping modes. Variable-speed technology has now been developed to allow operation of machines at variable speeds within a range of plus/minus several percent of synchronous speed, offering several technical advantages. Advantages include frequency control in pumping as well as in generating modes, improved efficiency in turbine operation, a greater operable load range, and very rapid response to load fluctuations in a network.

Various new developments are continuously evolving. In the near future the following innovations are anticipated:

- Two stage pump-turbines to operate beyond the current limits of maximum operating head.
- Reduction of the cost of adjustable speed units.
- Underground pumped storage, using underground caverns as the reservoirs.
- Seawater pumped storage plants.

Also the idea of offshore pumped storage plants, pumping between the sea and artificial sea water atolls at higher level, fully offshore or along the shore, has been proposed.

Interesting examples of pumped storage plants using seawater and/or underground storage follow.

*a) Seawater pumped storage plants*

Currently undeveloped sites that are suitable for the construction of hydropower plants are becoming increasingly difficult to find. As a result there is on-going research into new development options. One such project is that of a seawater pumped storage plant using the sea as the lower reservoir. Such a pilot plant was successfully constructed in Japan (See Reference 8 for details).

After basic research, site investigations and engineering studies, a 30 MW pilot test plant was constructed at Kunigami (Okinawa Prefecture). The octagonal upper reservoir, located nearly 600 m inland from the coast, is 25 m deep and has a capacity of 0.60 million $m^3$. The effective head of the plant is 136 m. Some features of the plant are shown in Figure 8.

Several technical and financial issues needed to be addressed. Financial issues included both construction cost considerations and on-going maintenance costs. Several technical solutions were introduced, some of which are listed below:

- Use of austenitic stainless steels, anticorrosive painting and cathodic protection to address corrosion problems.
- A closed circuit cooling system. As it is not possible to secure large quantities of freshwater as a coolant for the machinery, freshwater is circulated in a closed system. The freshwater in the closed system is cooled in a heat exchanger using seawater.
- Countermeasures had to be developed to discourage the adhesion of marine organisms inside the waterways.
- The upper reservoir was fully lined using a rubber membrane. Drains under the membrane serve to collect and discharge any possible leakage, to

prevent infiltration of salty water into the ground.

- Wave dissipating concrete blocks had to be placed around the sea outlet, to reduce wave-induced pressure fluctuations in the water conduits.
- The works had to be fenced to keep animals out. Inclined escape routes had to be provided to allow trapped animals easy escape from the fenced in areas.

Construction started in 1990 and the plant was commissioned in 1999. Ongoing monitoring and periodic inspections of the plant have confirmed that the plant is operating satisfactorily and that the salt water has not created any serious problems. The pilot plant served to confirm the validity of the adopted solutions and provides valuable precedents for future seawater pumped storage plants.

*b) Underground pumped storage plants*

An underground reservoir was constructed in Austria in 2006, to increase the operating storage for the existing Nassfeld pumped storage power station (See Reference 9 for details). The new underground reservoir extended the effective storage volume of the above ground Nassfeld daily reservoir, built in 1980-82, from 56 000 $m^3$ to about 230 000 $m^3$. The new reservoir comprises a network of underground caverns with a combined length of almost 2 000 m.

Several alternative solutions were studied before adopting the underground cavern solution. Some more conventional options to build a new off-stream reservoir, connected to the existing reservoir by waterways, were also studied. Difficulties associated with building a new surface reservoir in a conservation area, in close proximity to a National Park core zone, as well as operating restrictions resulting from avalanche hazards all made implementation of a conventional solution impossible. As a result, the unconventional solution comprising an additional underground storage cavern was finally selected.

The long mining tradition in the region, served to provide extensive documentation of the geological and geo-mechanical features of the area. A crucial consideration was the expectation that impermeable zones could be anticipated over large areas. Favourable conditions therefore existed for the construction of the underground cavern.

The new underground reservoir is adjacent to the existing above-ground daily reservoir, and the two are connected by a horseshoe-shaped tunnel as shown in Figure 9. The four, radially arranged, main caverns, each about 300 m long are interconnected by three transverse caverns, as shown in Figure 9. The typical height and width of the caverns are approximately 7.5 m and 15 m.

The total construction time was about 6 months, and the operation of the underground reservoir started in November 2006. The first cavern inspection took place in May 2008. Local collapses of up to about 3 $m^3$ were noted in three places. These local failures do not impact on operation in any way.

The new underground storage meets all the needs of the power station management and power traders, and has no impact on nature conservation interests in the area. The only visible evidence of the existence of the reservoir is the access portal. This is a very good example of finding an appropriate balance between commercial needs and environmental requirements. More such trade-off solutions will have to be found in the future.

# 3. KEY FEATURES OF HYDROELECTRICITY PRODUCTION

After more than a century of building and operating hydropower plants, there is a good understanding of both their benefits and disadvantages. The benefits are usually quietly accepted while the disadvantages are sometimes over-emphasized or publicised. At times such publicity is used to further the interests of other parties with different agendas.

A detailed presentation on the advantages and disadvantages of hydropower can be found in Reference 10.

A very comprehensive review concerning renewable energy sources and technologies, their relevant costs and benefits, and their potential role is given in Reference 53.

## 3.1. ANCILLARY SERVICES

To date most hydropower projects have been built to provide primary “base load” power generation into a power grid. However, as other less flexible (thermal and nuclear) and/or less predictable (solar and wind) generation technologies are introduced, hydro power production is increasingly being recognised for its ability to respond quickly to gaps between system demand and supply. Conventional hydro plants can be operated with lower load factors, thus preserving water in storage while there is surplus energy in the system. Such operation makes it theoretically possible to generate more power over shorter periods using the same volume of water stored. Often this benefit cannot be fully realised as the installed capacity of turbines become the limiting factor. In pumped storage plants this inherent benefit of hydro power is further enhanced as the power station stores surplus electrical energy available in a system during periods of low demand as potential energy which can then be made immediately available when the demand rises. This allows the optimization of base load generation from less flexible sources such as nuclear, thermal and geothermal plants, which can then continue to operate at constant levels at their best efficiency. It also facilitates stochastic power inputs from less predictable, renewable sources such as solar and wind power.

Thermal power plants require substantial amounts of energy and time for each start-up. Frequent start-ups and shutdowns may also significantly reduce the service life of such plant. Furthermore, the regulation velocity of thermal plants is limited, due to their high thermal inertia. Gas fired thermal plants have the highest level of flexibility for start-up and shutdown, and allow relatively rapid power variations. However, their minimum stable load (usually about 60% of full load, for open cycle plants and 25% for combined cycle plants) limits their regulation capacity to max 75% of rated power.

Hydro plants therefore remain as the most flexible plants for performing continuous and rapid start-ups and shutdowns. Hydro power plants reliably serve for primary, secondary and minute reserve (refer to ancillary services below). Their load variation speed is very high, the minimum load is low, often less than 2% of the installed power, and there is no fuel cost. Hydro plant are therefore the most flexible option to respond to gaps between supply and demand, meeting sudden fluctuations due to peak demand or loss of other power supply options.

In addition to the basic benefits described in the foregoing, hydropower can provide ancillary services to assist in assuring the stability of an electrical system. These services include:

- Spinning reserve, which is the ability to run at a zero load while synchronized to the electric system. When demand increases additional power can be loaded rapidly into the system to meet demand.
- Non-spinning reserve, which is the ability to enter load into the system from a source not on line. Some other energy sources can also provide non-spinning reserve, but hydropower's quick start capability is unparalleled.
- Regulation and frequency response, which is the ability to meet moment-to-moment fluctuations in system requirements. When a system is unable to respond properly to load changes, its frequency changes, resulting not just in a loss of power but potential damage to electrical equipment.
- Voltage support, which is the ability to control reactive power, thereby ensuring that power will continuously flow from generation to load.
- Black start capability, which is the ability to start generation without an outside source of power. This service may provide auxiliary power to other generation sources that could take long time to restart after a trip.

Obviously, the capability of a hydro power plant to provide all or some of these ancillary services depends on the type of machinery installed. Furthermore, the full set of the ancillary benefits described above are available from hydropower schemes with regulation reservoirs.

Run-of-river hydro power schemes, with little or no regulatory impoundment, simply contribute to base load generation, offering few of the ancillary benefits listed above. However, new developments demonstrate that it is possible to use run-off-river plants also for ancillary services by adopting a control technology which combines several power plants of a cascade into one virtual generation unit. See Reference 13 for further details.

Pumped-storage plants are particularly well suited to manage short term peaks in electricity demand, and to assure reserve generation for emergencies. They also have a significant environmental value as, without pumped storage, many thermal plants would operate at partial load as reserve generators. Such operation results in increased fuel consumption and an associated increase in the production of greenhouse gasses.

Pumped-storage plants can also absorb power when the system has an excess, thus levelling the load on the base load generators. Therefore, they are very effective to firm the variability of intermittent and stochastic renewable sources, such as wind power.

A small but interesting example of a fully integrated wind-hydro scheme is a project that is being planned in the Canaries' archipelago. The project will make the island of El Hierro, which has a surface area of 268 $Km^2$ and 10 000 inhabitants, completely self-sufficient using renewable sources only. The persistent trade winds will be harnessed to generate up to 11.50 MW using wind power plant. The wind generated electricity will be used to pump water into an elevated reservoir which will provide some 682 m head for hydro power generation. Electric energy will then be supplied from hydro power plant as needed. Any excess energy produced by the wind power plant will be used in two desalination plants to supply potable water needs. The project will replace the currently operating thermal plant which will remain as back-up source. It is estimated that similar projects could be effectively implemented on about a thousand islands across the world.

## 3.2. COSTS

### *a) Capital and Operation costs*

Hydropower plant converts potential and kinetic energy stored in water directly into electricity. The conversion process is very efficient. Modern hydro plants can convert more than 95% of water's energy into electricity, compared to the best fossil fuel plants that are about 60% efficient.

Hydropower requires large upfront investment. The high construction costs of dams, pressurized waterways, power stations that are often underground and appurtenant works all contribute to the large upfront capital investment that is required. This capital investment requirement often results in hydropower being labelled an "expensive option". However, comparing the benefits of a hydro scheme to that of any alternate technology simply on the basis of construction costs will often result in a less than optimum decision. More realistically options should be compared on the basis of life cycle costs. Such comparison should directly account for the differences in fuel, operating and maintenance costs over the lifetime of the scheme. Furthermore the comparison should also recognise other important differences such as reduced greenhouse gas emissions and the sustainability of the solution.

A useful indicator of the efficiency of a development alternative is the "Energy Payback Ratio", defined as the ratio of energy produced during the lifetime of the proposed plant, divided by the energy required to build, maintain and fuel the plant over its design life time. Hydropower almost invariably yields the best returns with respect to the Energy Payback Ratio. Refer to References 10 and 43 as well as to Figure 10 for further details. Hydropower schemes can produce in excess of 200 times the energy needed to build, maintain and operate them over their design life.  This is a much better return on investment than any other type of generation plant.

Numerous analyses confirm that hydropower is one of the least expensive renewable sources of electricity.  Some typical results are shown for illustrative purposes in Reference 31.  Also see the indicative results presented in Figure11.

Apart from the fact that the operating and maintenance costs of hydroelectricity are very low (typically a few percent of the capital costs), the plants operate without needing fuel.  This makes hydropower schemes totally immune to future fuel price variations.  As a result hydropower plants contribute significantly to "energy security", defined as "*uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers*" ("Green Paper" of the European Commission – EC 2000).

*b) External costs*

All forms of energy production create certain external costs.  External costs are costs that are not directly paid for by the producer or the consumer of the energy.  For example, greenhouse gases produced by burning fossil fuels result in external costs in the form of having to deal with global warming effects. Pollution resulting from the discard of used fuels may, in time, impose social costs in the form of increased health expenses, reduced agricultural productivity and the like.

Few mechanisms currently exist to realistically internalise external costs. As a result these costs are not properly reflected in energy prices.  Consumers, producers and decision makers therefore often do not get the realistic price signals that are necessary to make optimum decisions about how best to use resources.  This subject was investigated in a research project promoted by the European Commission ("*ExternE*", 2003, Reference 11). In this project detailed and comprehensive analyses were carried out to evaluate the external costs of various technologies for electricity generation.  The study considered seven types of consequences:

- Impact on human health – mortality;
- Impact on human health – morbidity;
- Impact on building material;
- Impact on crops;
- Impact on global warming;
- Amenity losses;
- Impact on ecosystems.

External costs were calculated using a bottom-up-approach.  Environmental consequences were estimated by following the chain from the source of emissions via air quality changes, soil and water pollution through to physical impacts, before being expressed as either monetary benefits or costs.

Following on from the original *ExternE* project, the methodology for calculating external costs has been further developed and improved in a number of projects, including *NewExt (2004), ExternE.Pol (2005) CAFE programme and MethodEx (2007).*

The most recent results (Reference 12) confirmed that the external costs of electricity production are still significant in most EU countries, despite the fall observed over the period 1990 to 2005 (primarily due to fuel switching away from coal to natural gas, ongoing improvement in generation efficiency, use of pollution abatement technology). In 2005 the average external costs in the EU were between 1,8 (low estimate) and 5,9 (high estimate) Eurocent/Kwh.

In terms of comparison among different sources, an excellent result for hydropower was pointed out. As resumed in Figure 12 the largest external costs resulted for coal and oil technologies; moderate external costs for gas and the lowest external costs, by an order of magnitude, for wind and hydropower.

*c) Compliance with planned costs, schedules and power delivery*

Reliable assessment of the financial and economic viability of a project is very dependent on the accuracy of estimates of construction cost, construction program and construction cash flow. Cost and/or construction programme overruns directly impacts on the project's effectiveness, particularly so for projects with high initial investment costs.

Hydropower projects are exposed, perhaps more than other projects, to the risk of construction cost and time overruns. Large dams, tunnels and often large underground caverns need to be constructed as part of a hydropower scheme. These structures are sensitive to various factors that might influence construction costs, construction programme and the planned power delivery date. Among such factors, the following are of particular interest:

- Geological and geotechnical conditions at the site are usually the most critical factors affecting cost and time. The quality of foundations, slope stability and the quality and volume of material in borrow pits for construction materials, may all show unexpected variations as construction progresses.
- During the long implementation period (design and construction), possible changes may occur in external conditions such as the economy, or changes in the regulatory framework and the like. Although such unexpected changes can usually be accommodated, they may result in an extended construction programme or in higher costs.

A study to evaluate 70 World Bank financed hydropower projects, commissioned between 1965 and 1986, found that the completion costs were, on average, 27% higher than those estimated at financial close. This result places hydropower projects in a better position than other dam projects. See Reference 4 for further details.

With regard to construction schedules, the study found that programmes typically overran by about 28%. Further details can be found in Reference 4. The average programme over runs are very similar to the results achieved for thermal power projects which are less affected by the previously described main factors influencing the risk for delays.

Another important aspect is the achievement or otherwise of the power generation specifications. Results show that hydropower projects perform quite well. The assessment of actual scheme performance versus targets, carried out by the WCD showed that, on average, hydropower projects have met expected targets, as shown in Figure 13.

## 3.3. ENVIRONMENTAL AND SOCIAL ISSUES

All infrastructure projects impact on the natural environment and on the local population. The question is whether the potential impacts are identified early enough in the project development cycle and whether they are then well managed and mitigated to the extent that the impacts are acceptable as part of the price of the development. International funding agencies and commercial banks recognise that development is always a compromise. To find acceptable balances for major infrastructure projects various institutions have established guidelines to be adhered to. Some of the guidelines are listed below:

- "*World Bank Group Environmental, Health, and Safety Guidelines*"
- "*International Finance Corporation (IFC) Performance Standards*";
- *"The Equator Principles*"

Dams and hydropower projects, by their nature store, divert and regulate the flow in rivers. Such interventions can have various environmental and social impacts. Each project would focus on offering significant benefits to the developers but the consequences for some stakeholders may be negative or harmful. Possible negative environmental and social impacts are discussed extensively in Reference 4.

The environmental and social aspects of hydropower projects are now understood to be a critical consideration during all phases of hydropower development regardless of scale or location. Much research has been directed at defining and understanding potential issues, their consequences and possible mitigation measures, aimed at avoiding or rectifying negative consequences and maximising positive outcomes.

The integration of environmental and social considerations in the planning, design and operation of dams and hydropower schemes is now a standard practice in most countries. The value of the early identification and analysis of potential environmental and social problems, right from the outset of a proposed project, is now recognised. These issues should be further analysed and debated in a comprehensive, inclusive negotiation process with all the interested and affected stakeholders. Such an inclusive approach through the project planning, design and implementation phases is now widely recognized to be of primary importance for effective project development.

It is worth recognising that there are many well-conceived hydropower schemes that have now been in beneficial service for several generations. Several dam sites have become sites of special interest because of the ecosystems that have successfully established in the reservoir areas.

*a) Guidelines*

As stated in the final Declaration adopted at the 2004 United Nations Symposium on "*Hydropower and Sustainable Development*", the dissemination of good practice and guidelines is recommended, to promote greater consideration of environmental and social aspects.

*World Commission on Dams*

The development of design criteria and guidelines was an integral part of the scope of work of the World Commission on Dams, established in 1998 and disbanded after the publication of its final Report. See Reference 4. Recommendations and a framework for decision-making were defined in the Report. Seven strategic priorities and policy principles form the core of these recommendations:

1) Gaining Public Acceptance, by recognizing rights, addressing risks, and safeguarding the entitlements of all groups of affected people, particularly vulnerable groups.
2) Comprehensive Options Assessment, identifying the most appropriate development response from a range of possible options.
3) Addressing Existing Dams, to optimize benefits from existing dams.
4) Sustaining Rivers and Livelihoods, avoiding-minimizing-mitigating the impacts to the river system.
5) Recognizing Entitlements and Sharing Benefits, through negotiations with adversely affected people.
6) Ensuring Compliance, meeting all the defined commitments.
7) Sharing Rivers for Peace, Development and Security, promoting mutual self-interest for regional co-operation and peaceful collaboration.

Several organizations, including ICOLD, pointed out that the WCD Report overlooked the benefits of dams and that the guidelines proposed in the WCD report for the planning and implementation of dam projects were too idealistic. It was argued that the WCD Report didn't fully recognise, or take into account, the different development phases in different countries.

In 2010 the United Nations Environment Programme carried out a snapshot survey to monitor the influence of the WCD report and guidelines. The survey attracted responses from many countries and a wide range of stakeholders. The results indicated extensive knowledge of the WCD recommendations and a widespread uptake of its principles in one form or another. Responses also highlighted several significant weaknesses in implementation. (See Reference 43).

*Guidelines by the European Union*

The "*Harmonized Guidelines and Template for Hydropower CDM Projects"* (Reference 18) was prepared by the European Union in 2009. All the European Union Member States agreed to use them for the assessment of large hydro projects. The *Guidelines* resulted from a process aimed to harmonize the Member States' assessment criteria, on a voluntary basis. They represent a regional sustainability assessment framework, aimed at ensuring that all projects are developed to be least damaging to the environment, and addressing public acceptance and equitable treatment of all affected stakeholders.

*Hydropower Sustainability Assessment Protocol*

An innovative approach has recently been launched to improve the sustainability of hydropower. The "*Hydropower Sustainability Assessment Protocol*" (Reference 17) was developed by a multi-stakeholder forum, comprising social and environmental NGOs, developed and developing country governments, commercial and development banks, and the hydropower sector represented by the International Hydropower Association (IHA). It builds on previous sustainability guidelines developed by IHA. It provides a comprehensive framework to assess the environmental, social, technical and economic/financial perspectives of new hydropower projects as well as the management of existing schemes. The *Protocol* identifies a range of approximately 20 topics which are relevant to all hydropower projects depending on their stage in the project lifecycle. It provides a consistent methodology for assessing sustainability globally.

The *Protocol* was formally adopted by IHA in November 2010. A multi-stakeholder governance structure, and terms and conditions for use have been established, to guide the implementation of the *Protocol* in the oncoming years. The *Protocol* has the support of large international institutions such as the European Commission (via funding from the LIFE programme), WWF and The Nature Conservancy.

The *Protocol* is not intended to be a 'pass' or 'fail' test. It guides users to consider and analyse the various sustainability issues. Scores are allocated for each topic in a range from 1 to 5, with 3 being basic good practice and 5 being proven best practice. The *Protocol* is divided into four main assessment tools:

- '*Early stage'* which is a preliminary screening tool to assess the strategic environment from which proposals for hydropower projects emerge. Nine topics are introduced for consideration.
- '*Preparation'* which assesses the preparation stage during which

investigations, planning and design are undertaken for all aspects of the project. Twenty three topics are introduced for consideration.

- ‘*Implementation’* which assesses the implementation stage, during which construction, resettlement, environmental and other management plans and commitments are implemented. Twenty 20 topics are introduced for consideration.
- ‘*Operation’* which assesses the operation of a hydropower facility. Nineteen topics are introduced for consideration.

*b) “Small Hydro - Large Hydro”*

Very often, particularly in the context of policies and incentives for the promotion of renewable energies, distinction is made between “large” and “small” hydro. Not all countries, or all development agencies, use the same criteria for this distinction. Small hydropower schemes are often defined as those with installed capacity of up to 10 MW, which are mainly run-of-river with little or no impoundment. Large hydropower schemes would then be schemes with installed capacity of 10 MW or greater, often with the inclusion of regulating storage.

The definition is, however, of great significance as “Small hydro” is usually considered a technology with low social/environmental impact. As a result “small hydro” is recognised among the “renewable energy” technologies to be promoted as green energy solutions. “Large hydro” is deemed to have significant impacts and therefore, even though it is renewable, it is often omitted from the list of green energy solutions.

From an environmental standpoint, the distinction between small and large dams/reservoirs is largely meaningless. All hydropower projects are renewable. It is not size that defines whether a project is sustainable or not, but the specific characteristics of the project. The way the project is planned, implemented and operated is of far greater significance than the size of the project.

The Political Declaration from the 2004 International Renewable Energies Conference (Bonn Conference) clearly states that ‘*In the context of renewables, renewable energy sources and technologies include: solar energy, wind energy, hydropower, biomass energy including bio-fuels, and geothermal energy*’. There is no mention of mega-watt limits as they relate to hydropower.

Furthermore, when small hydropower projects are compared with larger projects on the basis of equivalent electricity production, and the cumulative effects of many small schemes are considered, the environmental privilege of small over large hydropower becomes much less obvious.

There can be no doubt that small scale projects play an important role in remote areas, in rural electrification programmes, and in maximizing the value of multipurpose infrastructure. Larger schemes will however continue to be the most environmentally benign in supporting grid systems and powering industrial and urban centres. It should also be borne in mind that the large majority of population growth in the coming decades is likely to be centred in and around cities.

## 3.4. GREENHOUSE GAS EMISSIONS

The links between energy production and climate change are rapidly becoming more clearly understood and more widely accepted. Greenhouse gas (GHG) emissions, mainly produced by burning fossil fuels, are known to contribute to global warming. China and the USA currently produce the largest volumes of $CO_2$ emissions, contributing some 40% of the world total, followed by India and Russia, each producing about 5% of the world total (2008 data, from the "*Carbon Dioxide Information Analysis Centre*"[4]).

However, GHG emissions also come from many other sources including large water bodies, both natural and artificial. As water carries carbon in the natural cycle, all aquatic ecosystems (especially wetlands and seasonally flooded areas) emit GHG. The proportions of carbon dioxide and methane that are released to the atmosphere from water bodies depend on the specific site conditions, particularly the ecosystem and climate type. In slow-moving anoxic water bodies, the proportion of methane produced is increased. Methane is an important GHG because, according to the Intergovernmental Panel on Climate Change (IPCC, Reference 45), its global-warming potential is more than 20 times that of carbon dioxide over a 100-year time horizon.

The creation of an artificial reservoir modifies the chemistry of the flooded soils and leads to the release of labile carbon as well as nutrients into the water body. These nutrients enhance bacterial activity, and stimulate the overall production of the reservoir ecosystem, including the growth of plankton and the proliferation of fish communities. In addition, over the first few years of inundation, bacteria decompose part of the flooded organic matter, partly converting it to carbon dioxide and methane. These gases migrate through the water body, to be partly released to the atmosphere. The water residence time, the shape and volume of the reservoir and the amount and type of vegetation flooded, are some of the parameters which affect the duration of the emissions.

The concept of net GHG emissions is of fundamental importance for the assessment of the GHG status of man-made freshwater reservoirs. Net GHG emissions from man-made freshwater reservoirs are defined as the GHG impact from the creation of these reservoirs (or the GHG status of freshwater reservoirs). To properly quantify the net change of GHG exchange in a river basin caused by

[4] Organization within the US Department of Energy focused on data related to climate change and greenhouse gas emissions, and providing the research community with global warming data.

the creation of a reservoir, it is necessary to consider exchanges before, during and after its construction.  This means that net GHG emissions are the difference between the emissions with and without the reservoir, in the portion of the river basin affected by the reservoir, including upstream, downstream and estuarine areas.  In accordance with IPCC 2006 (Reference 46) the lifecycle assessment period for net GHG emissions should be 100 years.

Net emissions cannot be measured directly.  Results of field measurements are gross emissions which include the effects from natural and unrelated anthropogenic sources, both for pre- and post-impoundment conditions.

For a proposed artificial reservoir, the pre-impoundment emissions of the area should be evaluated, as a baseline to be compared with the emissions after impoundment.  Measurements after impoundment should take into account that the initial release of nutrients and the enhanced organic matter decomposition occur over a short period of time after the impoundment.  Emissions return to natural values, generally within 10 years for cold and temperate conditions, and within up to 30 years under tropical conditions.

The bulk of the currently available, published studies report large gross GHG emissions from new reservoirs only.  These results include, by implication, emissions from natural and unrelated anthropogenic sources.  They also disregard the natural reduction in GHG emissions over time.  Accordingly the published results generally lead to overestimates of GHG emissions over the reservoir lifetime.

The subject of GHG emissions from hydro reservoirs has become particularly popular among opponents to dams. They often refer to the case of the reservoir created by the Balbina Dam in Brazil (commissioned in 1989), for which very high GHG emissions were evaluated, due to its large flooded area per unit of generated electricity.  However, in general, hydropower presents a very low GHG footprint.  Studies in North America show that hydropower reservoirs tend to increase natural emissions marginally, and a value of 10 000 ton/TWh of $CO_2$ equivalent has been allocated to schemes in this region.  Considering that larger emissions should occur from reservoirs in warmer and tropical climates, a larger value (40 000 ton/TWh) has been proposed as an international average value for hydropower.  Neither of these values takes into account the sequestration of carbon in the reservoir sediments, so they are probably overestimates.

Even so, hydropower GHG emissions amount to only a few percent of any kind of conventional fossil-fuel thermal generation. This is clearly demonstrated in Figure 14, which shows the amount of $CO_2$ emitted by different electricity generating options. Data presented are based on a life-cycle analysis.

Another consideration recently introduced into the debate is the release of methane when the water emerges from the turbines, see Reference 19. The water at the bottom of a reservoir may contain a high concentration of methane under pressure. This methane would then be released when the pressure is suddenly released as the water emerges from the turbines. There is currently little data available to support this view.

The subject of GHG emissions from reservoirs is of particular interest for hydropower as it's becoming more and more important for carbon credits evaluation (see chapter 5). It must also be noted that a limited amount of monitoring data has been collected on this subject. Longer term monitoring will provide more reliable data. Therefore it is important to continue the monitoring efforts and the scientific work.

The International Hydrological Program of UNESCO (UNESCO-IHP) and the International Hydropower Association (IHA), with the collaboration of numerous research institutions, in 2008, started an international research project on GHG emissions from freshwater reservoirs. The research project, aims to improve understanding of the impact of reservoirs on natural GHG emissions, to obtain a better understanding of current methodologies and to help to overcome knowledge gaps. An important milestone was reached in 2010, with the publication of the "*GHG Measurement Guidelines for Freshwater Reservoirs*", a pioneering document that describes standardised procedures for field measurements and estimation of the impact of the creation of a reservoir on GHG emissions. These Guidelines put together the main products developed by the UNESCO/IHA GHG Research Project, using a consensus-based, scientific approach and an intensive international collaborative initiative. The report set the basis for the next stages of the research and for the application of the agreed protocols in the field. The methodology presented in the Guidelines is applicable for all reservoirs in all climate types. IHA's intention is to use the results to develop predictive tools, thereby reducing the necessity of intensive field measurements in the future.

Finally it's worth mentioning the research work completed and published in 2011 in "*Nature Geoscience*" (Reference 48). This research compiled the largest data set on greenhouse gas emissions from hydroelectric reservoirs available to date. Data was collected from 85 hydroelectric reservoirs across the globe. The data was collected and examined by an international team of scientists. The analyses concluded that the evaluated systems emit about 1/6 of the carbon dioxide and methane previously attributed to them.

# 4. HYDROPOWER DEVELOPMENT

The influence of the exploitation of the hydro potential of countries on their development is widely recognized.

A first interesting attempt to correlate the hydropower development with some development indexes was presented in Reference 47, examining the correlation between the percentage of developed hydro potential in Latin America countries and the "*Human Development Index*" (see Figure 15). This index, used to rank countries by level of human development, is a standard mean of measuring well-being (a comparative measure of life expectancy, literacy, education and standards of living). The correlation shown in the graph indicates the influence of the exploitation of the hydro potential on the development of the countries. The countries that had the chance to develop their hydro potential are now in a better position as regards development. In Reference 52 this analysis was extended to other countries. A tight relation was confirmed, as pointed out in Figure 16.

However, only one third of the world's potential hydropower resources have so far been developed. While in Europe and North America most of technically and economically feasible hydropower potential has been harnessed, large unexploited hydropower potential is available in Asia, where the current production is less than one third of the potential, and in Africa, where the ratio is even smaller (Figure 17).

## 4.1. WHERE THE HYDROPOWER POTENTIAL HAS BEEN EXPLOITED

In most of the countries where the hydro potential has been extensively harnessed the hydropower development started one century ago and many dams and plants are therefore old.

In these countries the focus is therefore on:

- maintaining ageing dams and reservoirs in a safe and efficient condition;
- managing new requirements and needs, minimizing the negative impact on power production;
- optimizing existing infrastructure.

*a) Safety and efficiency of the existing dams and reservoirs.*

The modernisation of existing hydropower plants is motivated and economically supported by the consequent additional or more efficient hydroelectric production. But maintaining existing dams and reservoirs in safe and efficient condition may require significant and expensive remedial works, conflicting with the available economic resources and limited duration of the concessions.

The most recurring problems are those related to the considerable length of service of many works:

- Obsolete dam design criteria which do not conform to current legislation compliance requirements or to the current state of the art.
- Increased or additional loads, arising from revised design criteria (larger seismic acceleration, larger maximum flood, sedimentation loads, etc.).
- Design criteria not fully compatible with current more demanding safety standards.
- Ageing and degradation processes, particularly the effect of expansive reactions within concrete (Alkali Silica Reaction or Alkali Aggregate Reaction). This effect currently accounts for one of the most significant causes of deterioration in concrete dams and hydro projects (Reference 20). It may give rise to shortcomings in both dam safety and proper working of the generation equipment.
- Silting of reservoirs, giving problems with the proper working of the outlets and intakes, and imposing additional loads on the structures.
  Hydropower reservoirs can generally be filled by sediments to a higher percentage than non-hydropower reservoirs, as they are largely used to maintain the head for power generation. However silting remains a problem in many cases requiring significant works for sediment removal.

Assuming that, on average, hydropower reservoirs are severely impacted when they reach a sedimentation level of 80%, the ICOLD Committee on "Sedimentation" put in evidence that this critical sedimentation level will occur, per region, as indicated in the following Table 6 (Reference 21):

| Region | Hydropower dams: Date 80% filled with sediment | Non-hydropower dams: Date 80% filled with sediment |
|---|---|---|
| Africa | 2100 | 2090 |
| Asia | 2035 | 2025 |
| Australasia | 2070 | 2080 |
| Central America | 2060 | 2040 |
| Europe and Russia | 2080 | 2060 |
| Middle East | 2060 | 2030 |
| North America | 2060 | 2070 |
| South America | 2080 | 2060 |

Table 6

In addition to the problems affecting dams, reservoirs and plants, most of the Countries where dam construction is diminishing have to face the problem of maintaining and preserving the hydropower and dam engineering professional expertise and ensuring that knowledge and experience are passed on to future generations.

*b) Additional requirements and purposes*

During the operating life of hydroelectric dams and reservoirs new demands are made on the system, additional to the original hydroelectric purpose. These include: flood protection, irrigation and potable supply, discharge for minimum environmental flow, recreational purposes and tourism development, wet land habitat, to name a few. These new needs introduce limitations and constraints in the use of the water often conflicting with the optimization of power production.

Continuous water discharge to assure minimum riparian environmental flow and to improve the downstream ecology is an example of new demands that can apply to most dams. Such new demands on the storage can reduce the electrical power production by a significant amount on the national scale. As a result, provision of new mini-hydro turbines to generate on the continuous discharge is receiving much interest to mitigate the effect of such storage loss.

The use of existing dams and reservoirs to manage and control runoff flows and protect downstream urbanized areas from large floods is an additional requirement frequently expected of hydropower dams and reservoirs. A significant example is the use for flood mitigation of the hydroelectric reservoirs located in the Paraná River basin, in Brazil (Reference 22). In this basin there is a large integrated reservoir system (46 reservoirs), having an installed capacity larger than 45 000 MW, including the Paraguayan share of Itaipu. Initially most of the reservoirs were designed for hydroelectric purposes only. Flood protection requirements were not considered at that time. More recently flood control legislation was established for all hydropower plants, to reduce the floods impacting downstream areas. Maximum outflow constraints were set for each reservoir and a flood-forecast system was developed via use of telemetry and meteorology. This entailed social and economic benefits through the reduction of flood impacts in the downstream areas. A trade-off between flood control and energy production was consequently made, since for electric power production it would be desirable to keep the reservoirs at their maximum capacity.

*c) Getting the most out of existing infrastructure*

Where most of the hydro potential has been harnessed and further development is limited to rather marginal contribution, the current focus is not on building new dams but rather tapping existing ones for their hydroelectric potential and getting the most out of existing infrastructure. This is accomplished through a variety of engineering strategies including the following:

- Upgrading existing schemes, and extending their operational life to take advantage of the long life of the civil structures.
- Optimizing the output of the plant to meet the needs of the power market.
- Adding capacity for extra generation when high flows are available.

- Adding small hydro facilities, to generate the discharge for the minimum environmental flow.
- Adding hydropower capabilities at non-power dams.

The last listed option, addition of hydropower capabilities at non-power dams, is an important option because the large majority of the dams in the world do not have a hydroelectric component. So, installing hydro power at these sites can offer a way to create new energy resources with minimal environmental impact.

With increasing incentives for the production of renewable energy, many owners are revisiting the possibilities of recovering energy from the transfer of water. The hydropower industry now offers an array of equipment suitable for these types of schemes.

*d) Development of intermittent renewable energy*

In many developed countries wind power generation has recently increased substantially, due to the increasing awareness about greenhouse gas emissions, and it now plays a significant role in the electricity systems of these countries. But wind by its nature is stochastic, wind power is produced independent of the demand, and wind power is constrained if winds are too gentle or too strong. Therefore it cannot accommodate societal electricity demand. The storage capacity of hydroelectric plants (particular by pumped storage plants, see par. 3.1) can be used to advantage in this context. The extensive development of intermittent "non programmable" renewable energy is increasing the need for pumped storage plants. This is clearly evidenced by a recent survey on the European market for pumped storage plants (Reference 49). This pointed out the major construction program that is going to be implemented in Europe for new pumped storage plants, to complement the increased production from renewable sources, in particular wind.

On average, European pumped storage plants are older than 30 years. Two-thirds of them were built between 1970 and 1990, and only 15 plants were built between 1990 and 2010. But, as shown in Figure 18, more pumped-storage plants will be constructed in Europe in the next 10 years than in any other previous decade. Most of the largest plants will be constructed in countries with large shares of wind energy, or in neighboring countries with appropriate topographical conditions.

## 4.2. WHERE LARGE HYDROPOWER POTENTIAL HAS STILL TO BE EXPLOITED

Among the countries with a large hydro potential still to be developed, in Asia and in South America the development is driven by leading countries with strong economic growth (China, Brazil, India, etc.).

In Eastern Asia the percentage of people with access to electricity is similar to that of the most developed countries, but in other parts of Asia there are many countries (Afghanistan, Nepal, Cambodia, Myanmar, North Korea, etc.) where this percentage is much lower. Regardless of stellar efforts and significant projects that are in progress for the development of new hydro capacity, only about 20% of hydropower potential has been developed in Asia. In Africa, where 65% of the population do not have access to electricity and the needs are consequently very urgent, only a very small amount of the hydroelectric potential has been harnessed.

In the last decade, after a period of serious difficulties and disputes, several important declarations have been adopted in favour of hydropower:

At the World Water Forum in Kyoto 2003, the most substantial effort to address the global warming problem, the Declaration of 170 Countries stated: '"*We recognise the role of hydropower as one of the renewable and clean energy sources, and that its potential should be realised in an environmentally sustainable and socially equitable manner*"'.

The 2004 Political Declaration adopted at the International Conference for Renewable Energies acknowledged that renewable energies, including hydropower, combined with enhanced energy efficiency, can contribute to sustainable development, providing access to energy and mitigating greenhouse gas emission.

At the 2004 United Nations Symposium on "Hydropower and Sustainable Development", the representatives of national and local governments, utilities, United Nations agencies, financial institutions, international organizations, non-government organizations, scientific community, international industry associations, made a strong Declaration in support of hydropower. Many important key points are clearly stated in this Declaration, among which are the following:

- the acknowledgement of the contribution made by hydropower to development, and the agreement that the large remaining potential can be harnessed to bring benefits to developing countries and to countries with economies in transition;
- the need to develop hydropower, along with the rehabilitation of existing facilities and the addition of hydropower to present and future water management systems;
- the importance of an integrated approach, considering that hydropower dams often can perform multiple functions;
- the acknowledgement of the progress made in developing policies, frameworks and guidelines for the evaluation and mitigation of environmental and social impacts, and the call to disseminate them.

Finally, in 2008 a "*World Declaration – Dams and Hydropower for African Sustainable Development*" has been approved by the African Union, the Union of Producers Transporters and Distributors of Electric Power in Africa, the World

Energy Council, the International Commission on Large Dams, the International Commission on Irrigation and Drainage, and the International Hydropower Association.

As pointed out in this World Declaration, the current condition is now ripe for hydropower development in Africa. A new commitment and political will exist today and more projects are under development, as clearly shown by the graph reported in Figure 19.

International lenders are now supporting dams and reservoirs, after a period of stagnant investment. World Bank lending for hydropower reached a low point in 1999, as clearly shown in Figure 20, as a consequence of the strong debate about the environmental and social concerns and the critical assessment of role of hydropower. This debate stimulated the evaluation of acceptable hydropower recognizing the core principles of sustainable development (the "three bottom lines" approach: social-environmental-economic).

The need of significant levels of investment in water infrastructure throughout the developing world was stated in the "Water Resources Sector Strategy" approved by Board of the World Bank Group (WBG) in 2003, and was supported in the subsequent WBG's Action Plan and Frameworks (Reference 25, Reference 26, and Reference 27). The current World Bank Directions states that hydropower is viewed as an integral factor in addressing energy security, climate change, water security, and regional cooperation (Reference 28).

The WBG's current lending reflects this re-engagement, as clearly shown in Figure 20. World Bank Group now supports a range of hydropower investments, from small run-of-river to rehabilitation and to multipurpose projects. Run-of-river projects currently account for the largest portion of the portfolio, in both value and number of projects; storage projects (24%) and rehabilitation projects (28%) account for the remaining half of the portfolio.

Although many NGOs still remain critical and cautious, with respect to hydropower development there is a growing openness towards considering hydropower's potential contribution to meeting energy demands. The W.W.F., for example has included 400 GW of hydropower in its recent energy scenario for climate change (Reference 29).

*a) Hydropower in integrated water resources management*

Currently it may not be acceptable simply to maximize the economic profits of a hydroelectric scheme. There is now a major worldwide focus on integrated water resources management, highlighting the multiple benefits of dams and reservoirs. Therefore, closer linkages between water and energy resources are required, and the increasing need for an effective water management may also be the most effective driver for hydropower development.

As part of well-planned water resources infrastructure, in which design and operation are considered at the catchment scale, hydropower can help countries to manage floods and droughts, and improve water resources allocation across a complex set of users.

The hydropower components of dams and water storage schemes tend to perform better financially than associated irrigation projects, which often fail to recover operating and capital costs. Thus, the power element cross-subsidizes irrigation, navigation, flood control, etc. In the United States this kind of cross-subsidy was a planned part of the management of the Grand Coulee Dam in the Columbia River Basin and of the major river basin development works of the Tennessee Valley Authority (Reference 50).

The case history of Kafue Flats, in Zambia, offers another good example of the importance of a water management plan set up with the contribution of all the involved stakeholders (Reference 50). Kafue Flats is a rich wildlife habitat sustaining the livelihoods of local people when floods recede on the flats at the end of the wet season. In 1978 the Itezhi-tezhi dam was built to store wet season peak flows, to maximize hydropower production at the Kafue Gorge hydroelectric dam, Zambia's primary source of power. The Itezhi-tezhi dam ended the beneficial wet season flooding of Kafue Flats, adversely affecting 300 000 local people. In 1999 a project was initiated, to restore a more natural flow from the Itezhi-tezhi Dam. An integrated water resources management plan was studied and an agreement was reached in 2004 among all the partners to implement new dam operating rules. The long-term results are expected to include improved ecological health for Kafue Flats and improved livelihoods for local people, development of a wildlife-based tourism industry and sustained irrigation capacity. The hydroelectric production potential of the Kafue Gorge Dam is expected to be maintained or to increase.

This example emphasizes that an integrated water resources management also provides a context in which the impacts and true value of a dam may be assessed, taking into account multiple objectives, including both economic and non-economic benefits.

The development of effective integrated water resources management must be based on a strategic national plan, and for large river basins affecting more than one country the national level may not appropriate for proper planning. Good practice in managing water resources demands a river basin approach, regardless of national borders. In these cases multinational cooperation is therefore called for and of paramount importance. In developing markets interconnection between countries and the formation of power pools will build investor confidence.

*b) International cooperation*

International cooperation is a key element for the development of hydropower in many developing countries, and in recent times international and regional cooperation has increased for hydropower development. For example, companies from some Asian countries with major experience in hydro development, such as China and Iran, are investing in schemes in Africa. In South and East Asia a number of bi-national developments are moving ahead, based on power purchase agreements, enabling some of the less developed countries to gain economic benefits from exporting their hydropower production to trigger its development. The Nam Theun project, in Laos, is a clear example: most of the power will go from Laos to Thailand.

In Africa international cooperation in the development of shared water resources is of major importance, considering that Africa has 61 international shared rivers, whose basins cover about 60% of the surface of the continent. As an example, the West Africa Power Pool Project is the vehicle designed to ensure the stable supply of electricity to member countries of the Economic Community of West Africa States, beginning with four member nations, namely Niger, Ghana, Benin and Togo. The first phase of the project is a 70 km transmission line linking Nigeria to the Republic of Benin (Reference 30).

An excellent example in Africa of the tremendous potential available in developing countries, and the need of strong international cooperation to develop it, is the Grand Inga project, on the Congo River. The project has been under discussion for a long time, the first studies being carried out in the 1960’s. As proposed, the project should have an installed capacity close to 40 000 MW and an estimated production capacity of more than 280 TWh/year, with a very low cost of the generated energy. In addition, the estimated environmental impacts are low, particularly when compared with the environmental benefits of the project. Grand Inga could save more than 100 million tons of fossil fuel each year. The huge generating capacity is a result of the huge average annual flow (~40 000 $m^3/s$) and the fact that the river drops almost 100 m in just 13 km. The site is centrally positioned on the African continent, thus making it feasible to serve a large regional population.

## 4.3. POLICIES AND PROGRAMS

Defining energy policy and creating the conditions for renewable energy development is in the competence of the national governments. National governments can also agree to harmonise or coordinate their policies with those undertaken by other countries in the framework of a community of countries (such as the European Union), in order to increase coherence and effectiveness of their individual energy policies.

Different measures are available to promote the development of renewable energy in the electricity generation market, including:

- Mandated market policies, which set mandatory quantities in the form of quotas or mandatory prices such as feed-in tariffs.
  Competitive bidding for renewable energy concessions and green energy tradable certificates are also considered to be mandated market policies.
- Financial incentives, focused on improving the competitiveness of renewable energy technologies: capital grants, investment/production tax credits, property tax exemptions, sales tax rebates, etc.

Taxes on fossil fuels also improve the competitive position of renewable energy and are particularly appropriate to internalize negative external effects on environmental or energy security.

- Preferential public investments for renewable energies in government procurement, infrastructure projects, etc., which combine renewable energy growth stimulation with development programs.

The International Energy Agency, with support from the European Commission, provides a "*Global Renewable Energy Policies and Measures Database*", which currently covers more than 100 countries and categorises the measures according to 14 different technologies and 24 policy types. The database includes measures in IEA member countries, together with members of the Johannesburg Renewable Energy Coalition (JREC), and Brazil, China, the European Union, India, Mexico, Russia and South Africa. Containing more than 1000 records dating back to 2000 and even earlier, the database provides an excellent source of information to support decision makers, policy experts and researchers, as well as providing practical information to the business community and the broader public.

Policy targets for renewable energy have been defined, supplemented and revised in a number of countries, based on the environmental targets defined in the Kyoto protocol. As an example, the directive issued in 2001 by the European Union for promoting renewables in electricity generation sets targets for individual member states and at European level. The targets are shaped following the objectives of climate change mitigation and ensuring the fulfilment of European commitments to the Kyoto protocol. The EU does not strictly enforce these targets, but the member states' progress is monitored, and targets for those who miss their goals can be proposed.

Regardless, a comparative analysis of the promotion policies in 35 countries, completed in 2008 by the International Energy Agency (Reference 32), concluded that "only a limited set of countries have implemented support policies for renewables, and there is a large potential for improvement".

*a) Carbon Credit Market*

Emissions trading is a market-based approach (also known as "*cap and trade*") providing incentives for achieving reduction in the emission of pollutants. Carbon emissions trading is specifically addressed to the reduction of carbon dioxide ($CO_2$) and currently makes the bulk of emissions trading.

In this trading a central authority set a limit on the amount of the pollutant that can be emitted (the "*cap")*, usually lowered over time aiming toward emissions reduction. The cap is allocated to firms in the form of emission permits ("*credits")*. Firms that need to increase their emissions must buy permits from those who need fewer permits. So, the buyer pays a charge for polluting, while the seller is rewarded for having reduced emissions.

In the Kyoto Protocol most developed nations agreed to legally binding targets for their greenhouse gases emissions, and emission quotas were agreed by each participating country.

To enable industrialized countries to acquire greenhouse gas reduction credits to be used to meet emission reduction targets, the Kyoto Protocol provides for three mechanisms:

- International Emissions Trading: countries can trade in the international carbon credit market to cover their shortfall in allowances.
- Joint Implementation: a developed country with relatively high costs of domestic greenhouse reduction would set up a project in another developed country.
- Clean Development Mechanism (CDM): a developed country can 'sponsor' a greenhouse gas reduction project in a developing country where the cost of the project is usually much lower, but the atmospheric effect is globally equivalent. The developed country would be given credits for meeting its emission reduction targets, while the developing country would receive the capital investment and clean technology.

Consequently, most worldwide carbon transactions take currently one of the following two forms (see Figure 21):

- Allowance based trading, in which the buyer purchases emissions allowances created and allocated by regulators under “cap and trade” regimes. This trading is primarily driven by the European Union Emission Trading Scheme, the largest multi-national emission scheme, accounting for about two thirds of the worldwide carbon market. This Trading Scheme was already operational when the Kyoto Protocol came into force; the European Union later agreed to incorporate Kyoto flexible mechanism certificates as compliance tools within the E.U. Emission Trading Scheme.
- Project-based trading, in which the buyer purchases emissions credits from a project that can demonstrate that it reduces GHG emissions compared to what would happen otherwise. Most project-based trading is currently executed through the CDM.

CDM projects have to demonstrate a high level of sustainability. Rules have been specified to check that the project reduces emissions more than would have occurred in the absence of the project, that the planned reductions would not occur without the incentive provided by emission reductions credits, and that the project results in real, measurable, and long-term emission reductions.

CDM projects cover a wide array of sectors and technologies involving energy generation and consumption. Hydropower is the CDM’s leading deployed renewable energy; about 25% of the total CDM projects registered since 2004 are hydropower projects (the next largest categories are “Methane avoidance”, “Wind” and “Biomass energy”, each with 14-15% of the total).

China (more than 60 %), India (11%) and Brazil (6%) are the top three host countries. Despite Africa's large undeveloped resources, very few hydropower projects have been registered in Africa to date.

However, in recent years, criticism against the mechanism has increased. NGOs have criticized the inclusion of large hydropower projects as CDM projects, and the European Union Emission Trading System has placed certain restrictions on the recognition of projects exceeding 20 MW.

*b) The influence of financing models*

The development of appropriate financing models and the definition of an optimum role for the public and private sectors are major challenges for hydropower development, as clearly pointed out and discussed in Reference 34. The global trend in the financing of infrastructure projects is inexorably directed towards increasing dependence on private investment. Of course, for the attraction of resources from the private sector several conditions are required: reliable policies and institutions, adequate payments from energy consumers, clear and stable regulations for developing and operating hydro plants, financial structures that support public-private partnership projects.

In general private hydropower projects are developed on a BOT basis (build, operate, transfer), with the scheme eventually reverting to the utility at the end of the concession period. Under such arrangements it is natural that a private concessionaire takes a shorter-term and narrower perspective which may be in conflict with broader interests.

For example, many private projects are promoted as run-of-river schemes (to facilitate the authorization process, to minimize the possibility of opposition related to social and environmental concerns, and to favour the involvement of financiers and guarantee agencies), irrespective of whether the site might be better developed as storage project yielding higher quality production and possible multipurpose benefits.

From a public good perspective, governments need to undertake strategic assessments and feasibility studies in order to develop a pipeline of projects and identify high value storage sites. Irrespective of the source or arrangements for financing, the public sector must play an important role in the development of hydropower projects. Although the arrangements will vary from country to country and from project to project, the support of the host government will continue to have a strong influence on most future hydro projects. If the private investor is to be attracted, the public sector has to be prepared to assume some of the risks, and to play a large role in the projects.

# 5. TIDAL POWER DEVELOPMENT

## 5.1. INTRODUCTION

Tidal power offers a practically inexhaustible and renewable energy source. Although not yet widely used, tidal power has a significant potential for electricity generation. Today much attention is focusing on tidal energy, as a result of the strong attention to renewable and clean sources of energy (see Reference 36).

The overview of world prospects for tidal power development indicates that a huge cost-effective potential (in the order of 1 000 TWh/year) could be developed in the foreseeable future, with minimal environmental and social impacts compared with any conventional land based power plants on such scale.

Five countries have a huge cost effective potential in the range of 100 TWH/year or more: Australia, Canada, China, France, and Russia. At least 10 other countries have a significant potential: Argentina, the U.S., Colombia, Brazil, Chile, the U.K., India, Bangladesh, Myanmar and Korea (Reference 37).

Compared with wind and sun energies, tidal energy has the advantage of being well known in advance. Monthly tidal energy will remain the same throughout the year and its annual supply is much more reliable than most traditional hydropower. The tidal range varies over two weeks and the energy from one week may be three times the energy of the other. The optimum storage of tidal energy is therefore not limited to a tide but should be efficient over two weeks.

The power potential of a tidal basin is proportional to the surface area of the basin and to the square of the mean amplitude of the tide. Tidal flows in bays and rivers present the most effective way of utilizing tidal power through the construction of low-head tidal barrages.

The tidal power development began in sixties, with Rance plant in France (1966) and Kislogubskaya plant in Russia (1968). The construction of large tidal schemes has been severely restricted by the high costs of traditional dam construction (involving cofferdams). Tidal power plants have high capital costs and a very low running cost. As a result, a tidal power scheme may not produce returns for many years, and investors may be reluctant to participate in such projects due to the lag time before investment return and the high irreversible commitment. However, new design solutions and new construction methods are contributing to the reduction of construction costs and can support a more extensive use of tidal energy in the future (Reference 38).

Similarly to conventional dams for hydropower, barrage systems for tidal power are affected by possible environmental problems associated with the modification of very large ecosystems.

The following solutions can be adopted for the generation of electricity from tidal energy:

- making use of the potential energy in the difference in head between high and low tides, by means of barrages located across the full width of a tidal estuary;
- as above, but using tidal lagoons, so avoiding a complete closure of an estuary/bay;
- making use of the kinetic energy of moving water by means of tidal stream systems, in a similar way to windmills that use moving air.

More detailed information is given hereinafter about the solutions making use of dams.

## 5.2. DAMS FOR TIDAL POWER

The use of dams for the production of hydroelectricity from tidal energy involves building a barrage across a bay or river. The dam/dike generates a difference between the water level outside and inside the basin, and turbines installed in the barrage generate power as water flows in and out of the estuary basin, bay, or river.

The basic elements of a barrage are, in a general configuration: caissons (very large concrete blocks), dikes, sluices, turbines, and ship locks. Sluices, turbines, and ship locks are housed in caissons.

The dikes will operate at low heads and some leakage may be acceptable. The loads from waves may be larger than the loads from differential head, and are a key condition for construction methods.

Many designs are possible, depending on available local material. Dykes may be constructed using:

- Rockfill dykes with concrete block protection, designed not to be overtopped. Significant volumes of rockfill quantities may be required and design must consider provision for seepage loss and control.
- Prefabricated concrete caissons designed not to be overtopped.
- Traditional breakwaters of rockfill or prefabricated caissons which are designed to be overtopped at high tides, along with wide low cost granular fill dykes built in calm water by large sea dredges.

### *a) Basins Layout and operating schemes*

Some general key points are the following:

- all projects will probably be along shores; completely offshore projects are more expensive, with longer dykes and more expensive access;
- the cost and efficiency of the turbines depend on the average operating head and on the operation scheme (one-way, two-way);

- the use of pumping facilities may increase the energy supply and flexibility of operation, but their cost may offset this advantage.

The basic solution for a tidal power plant refers to a single basin layout. It can be operated according to “one-way” or “two-way” scheme (see Figure 22):

- *One-way*: The basin is filled through the sluices until high tide. Then the sluice gates are closed. (At this stage there may be "pumping" to raise the level further). The turbine gates are kept closed until the sea level falls to create sufficient head across the barrage, and then are opened so that the turbines generate until the differential head is again low. Then the sluices are opened, turbines disconnected and the basin is filled again.
- *Two-way*: In addition to the one-way generation, the basin is filled through the turbines which also generate power in this phase. This phase is generally less efficient because the differential head on the filling and emptying cycles is less than for one-way operation.

*b) Materials*

Construction materials for tidal plants are very similar to those used for marine hydraulic structures. They must withstand harsh marine conditions. Protection of the steel structures from corrosion can be achieved by cathodic protection systems. In very cold sites, in addition to high strength and high imperviousness, concrete structures have to be specially designed to be frost resistant.

Furthermore, concrete structures and metal equipment must be protected against the biological influence of the seawater (bio-fouling). To this aim, “non-fouling” concrete has been developed, containing biocidal admixtures that are progressively released into the water, so providing 10-12 years of non-fouling protection cover, significantly improving the 1-2 years protection provided by non-fouling toxins applied as thinly painted coat. But the long service life of the plant requires further solutions. An electrochemical electrolyser, pumping seawater to form a chlorine solution, was successfully tested at Kislogubskaya plant to protect the penstock against bio-fouling.

*c) Turbines*

A key problem is the choice of turbines which will operate under low heads, possibly both ways and with or without pumping facilities. Their cost and performance and construction facilities may vary considerably.

Bulb Turbine units have many advantages but they become very expensive for low heads (tidal range under 6 m). They may be used for turbining in one direction or in two directions with pumping possibilities.

The more recent solution of orthogonal turbines appears promising for operating both ways (even with low heads and average tidal range of 4 or 5 m). They cannot pump. The lower cost of the orthogonal turbines is achieved by a reduction of the mass of the main hydropower equipment, as well as cheap technology for blade production (by rolling). Furthermore, the orthogonal unit avoids the need to construct water discharge facilities, and also this fact considerably contributes to reducing the cost of the plant construction. In total, a cost saving up to 30% has been estimated.

The orthogonal turbine has a design maximum efficiency of 0.70 - 0.75, lower than the efficiency of bulb turbines (0.90). However the output of orthogonal turbines does not vary much with head, and is the same in both directions. It seems therefore that the average efficiency is lower than for bulb units if operating one way, and similar or better if operating both ways.

*d) Environmental impact*

Tidal plants offer the advantages of being non polluting, they do not cause the loss of land or the need for resettlement. Also, in the event of failure of a barrage there is practically no threat to life or property (unless the barrage is aimed also to provide protection to a low-lying hinterland prone to flooding).

Beyond these inherent advantages, the possible negative environmental effects must be evaluated. The placement of a barrage into an estuary has a considerable effect on the water inside the basin and on the ecosystem. The construction of tidal plants alters the flow of saltwater in and out of estuaries, which changes the hydrology and salinity and possibly negatively affects the marine mammals that use the estuaries as their habitat. Turbidity (the amount of matter in suspension in the water) decreases as a result of smaller volume of water being exchanged between the basin and the sea. This lets light from the sun penetrate the water further, improving conditions for the phytoplankton. The changes propagate up the food chain, causing a general change in the ecosystem.

At the Rance plant, in France, the first tidal barrage plant in the world, a full-scale evaluation of the ecological impact of a tidal power system operating for many years has been made. French researchers found that the isolation of the estuary during the construction phases of the barrage was detrimental to flora and fauna, however; after ten years, there has been a variable degree of biological adjustment to the new environmental conditions. Some species lost their habitat due to plant construction, but other species colonized the abandoned space, which caused a shift in diversity. Also as a result of the construction, sandbanks disappeared, a beach was badly damaged and high-speed currents have developed near sluices.

The careful environmental monitoring and studies carried out at

Kislogubskaya tidal plant, in Russia, pointed out that after four decades of operation the gulf is almost ecologically stable, and that the system which is forming differs from the initial one.

Littoral zones can be considered as those of greatest ecological risk, because of the possible intensive desalinating of sea waters. Depressions or hollows can also be considered zones of ecological risk, because of the deficiency of oxygen.

Estuaries often have high volume of sediments moving through them, from the rivers to the sea. The introduction of a barrage into an estuary may result in sediment accumulation within the barrage, affecting the ecosystem and also the operation of the barrage.

Fish may move safely through sluices, but when these are closed, fish will seek out turbines and attempt to swim through them. Also, some fish will be unable to escape the water speed near a turbine and will be sucked through. Experiments on passing fish through the turbines with subsequent capture showed that food fish (99% of all amount) pass undamaged through low-head runners of capsular and orthogonal hydraulic units with rotation speed of 40-72 rpm. Alternative passage technologies (fish ladders, fish lifts, fish escalators etc.) have been introduced to mitigate this problem. Research in sonic guidance of fish is also ongoing.

## 5.3. TIDAL POWER PLANTS

Several tidal power plants are currently in operation. Some others are in the design-planning phase. A summarised description of some interesting power plant is given hereafter.

### *a) Rance Power Plant - France*

The Rance Tidal Power Station (Figure 23) is located on the estuary of the Rance River, in Brittany, France.

Opened in 1966 after six years of construction, it is currently operated by Électricité de France, and is one of the largest tidal power station in the world: 24 turbines, bulb units, installed capacity 240 MW. The tide fills and empties the estuary twice a day, reaching a maximum flow rate of 18 000 $m^3/s$. The turbines are designed to operate “two-ways”, producing electricity during both the filling and the emptying of the basin. The annual output is about 600 GWh.

The tidal basin measures 22.5 $km^2$. The mean tidal amplitude is 4 m.

The barrage is 750 m long and 13 m high. The power plant portion of the dam is 390 m long. The plant was built on rock, in the dry, behind temporary cofferdams.

A canal lock in the west end of the dam, 65 m long and 13 m wide, permits the passage of 16 000 vessels between the English Channel and the Rance. A highway crosses the dam and there is a drawbridge where the road crosses the lock which may be raised to allow larger vessels to pass.

The high development costs of the project have now been recovered and electricity production costs are lower than that of nuclear power generation.

Since its construction a new ecological equilibrium was established in the estuary. There is an abundance of fish, of different species. The operation of the plant also facilitates boating in the estuary, being the mean water level higher than it was before the construction of the plant.

The facility has become also a tourist attraction, attracting many visitors

*b) Annapolis Royal Power Plant - Canada*

The first tidal power in North America is the Annapolis Royal Generating Station, Annapolis Royal, Nova Scotia, on an inlet of the Bay of Fundy. The mean tidal amplitude is 3.2 m. The basin area is 6 $km^2$. The plant opened in 1984. It has 18 MW installed capacity.

Tidal schemes to generate electricity had been under discussion for the Bay of Fundy for several decades. The decision to build the facility was partly prompted by the federal government funding for this alternative energy project, as well as the provincial requirement of the Department of Transportation to replace an aging steel truss bridge over the river between Annapolis Royal and Granville Ferry.

*c) Kislaya Guba Power Plant – Russia*

The 0.5 MW *Kislaya Guba* project was built between 1964 and 1968 in the Kislaya Bay of the Barents Sea. The plant adopted a French bulb unit. It is the first example of a floating hydropower plant with the powerhouse constructed in a yard and then towed by sea to the site where it was mounted on an underwater foundation bed.

In 2004-2007 it was upgraded installing an orthogonal turbine, in a second conduit left empty at the time of construction. A first orthogonal turbine (horizontal axis, 2.5 m diameter runner) was installed in 2004. Then, taking into account the experience derived, a larger turbine (vertical axis, 5 m diameter runner) was developed and installed. The generation unit was transported by floating to the site, and special measures were used for positioning and ballasting so that the floating generation unit could be set down on its subsea platform with a high degree of accuracy (the offset of the centre of the unit from the designed position should not exceed 0.05 m and the angle of deviation of its axis should not exceed 0.1°).

The placing of the turbine shaft perpendicular to the flow not only permits the placement of the generator and step-up gear outside of the turbine chamber but also the mounting of several runners on a single common shaft, that is a multi-stage turbine with one common generator. The rotational direction of the runner does not change when the direction of the flow though the turbine changes.

*d) Sihwa Lake Power Plant and Uldolmok Power Plant– South Korea*

Built on the shores of Sihwa Lake, in South Korea, the Sihwa Lake Tidal Power Station (Figure 24) is the current largest tidal power station in the world, with a total power output capacity of 254 MW (Reference 4, Reference 54).

The power is produced by ten submerged bulb turbines, 25.4 MW each, driven by 60 000 million $m^3$ annual tidal flow, generating power on tidal inflows only ("one way" scheme).

Mean tidal range is 5.6 m, with a spring tidal range of 7.8 m. The basin area, reduced by land reclamation and freshwater dykes, is about 30 $km^2$.

The barrage makes use of a seawall constructed in 1994 for flood mitigation and agricultural purposes, and that should provide an indirect environmental benefit. In fact, after the seawall was built, pollution built up in the newly created reservoir making the water useless for agriculture, and in 2004, seawater was reintroduced into the reservoir in the hope of flushing out contamination; inflow from the tidal barrage is envisaged as a complementary permanent solution.

The project was funded by the South Korean government, with some funds coming from Korean private firms. The station was completed in 2010, and became fully operational in 2011.

The Uldolmok Power Plant is the first tidal power plant in South Korea, at Jindo Island, South Jeolla Province. It is a plant which is planned to be expanded progressively to 90 MW of capacity by 2013. The first 1 MW was installed in 2009, producing about 2.4 GWh/year. Additional 0.5 MW capacity was commissioned in 2011.

*e) The Severn Barrage – United Kingdom*

The Severn Barrage is any of a number of ideas for building a barrage from the English coast to the Welsh coast over the Severn tidal estuary. The tidal range in the Severn Estuary is the second highest in the world, averaging about 13 m.

Ideas for damming or barraging the Severn estuary have existed since the 19th century, with various purposes: transport links, flood protection, harbour creation, tidal power generation. In recent decades the latter has grown to be the primary focus for barrage ideas, and the others are now seen as useful side-effects.

Following on from the conclusions of the "Sustainable Development Commission" (2007) the UK Government has undertaken a Tidal Power feasibility study, considering all tidal range technologies. In the first phase of this study several potential options were evaluated, and an affordable and feasible shortlist has been established for more detailed future studies. The shortlisted options are (see Figure 25):

- Cardiff to Weston Barrage
- Shoots Barrage
- Beachley Barrage
- Welsh Grounds Lagoon
- Bridgwater Bay Lagoon

The Cardiff to Weston-super-Mare barrage is the largest option, stretching about 10 miles and impounding an area of 185 square miles. It would enable to save 7.2 Mt of $CO_2$ per year. The installed capacity would be 8 640 MW (Reference 39). Because of the environmental impact of the barrage solution, tidal lagoons solutions are also considered in the shortlisted options. The lagoons would not directly impound the ecologically highly valuable inter-tidal areas of the estuary (an environmentally protected area, proposed for Special Area for Conservation designation in recognition of the European importance of its ecology).

Subsequent studies are needed to refine the evaluation of the shortlisted schemes, and to explore mitigation options. Identification of mitigation measures will not be straightforward due to the often contradictory set of requirements (inter-tidal habitats, fish, ports and navigation, land drainage, flood defence, construction impact, long term impact, etc.).

Following the conclusion of the feasibility study, the Government concluded that it does not see a strategic case for public investment in a tidal energy scheme in the Severn estuary at this time, but wishes to keep the option open for future consideration. This decision has been taken in the context of wider climate and energy goals, including consideration of the relative costs, benefits and impacts of a Severn tidal power scheme, as compared to other options for generating low carbon electricity. The outcome of the feasibility study does not preclude a privately financed scheme coming forward in the meantime, and Government is talking to private sector consortia and individual companies about their ideas.

The decision not to rule out a scheme in the longer term recognizes the significant UK resource that the Severn estuary presents. It represents a renewable, predictable resource with the potential (through a tidal power scheme) to generate up to 5% of the UK's electricity needs, and so potentially make an important contribution to the UK's renewable energy targets.

*f) Mersey Estuary – United Kingdom*

Feasibility studies are in progress also for the Mersey estuary (Reference 40). This estuary has one of the largest tidal ranges in the UK, and a tidal scheme in this estuary could satisfy the electricity needs of a large part of the Liverpool City region.

A noteworthy feature of the Mersey estuary, which makes it attractive for a tidal power project, is its narrow mouth. While most estuaries tend to become progressively wider toward the sea, in the Mersey estuary a narrow area (1-2 Km width) extends from the estuary mouth to an area upstream; therefore moving the location of a tidal plant in the seaward direction increases the quantity of water commanded and of energy captured and reduces the length of the barrage.

*g) Jiangxia and Yalu Project - China*

The Jiangxia plant is located in Wuyantou, Zhejiang Province, China. The current installed capacity is 3.2 MW. The facility generates up to 6.5 GWh of power annually. The maximum tidal range in the estuary is 8.4 m. The power station feeds the energy demand of small villages at a 20 km distance, through a 35 kV transmission line.

In the context of the efforts to add renewable energy to the mix, the Chinese government signed an agreement for a renewable energy 300 MW tidal project near the mouth of the Yalu River. Next steps for the project are to conduct engineering feasibility studies.

## 6. CASE HISTORIES (SOURCES OF INFORMATION)

To properly address adverse environmental, social, and economic impacts associated with hydropower development and optimizing the benefits obtained, it is clearly important to use the latest technology and knowledge in devising “tailor-made” impact mitigation and enhancement measures to suit specific circumstances of the project, but, first of all, it is necessary to learn from past experience.

Information on Good Practices in the design, construction, operation and refurbishment of hydropower projects, should be shared by the technical communities around the world, to contribute to an effective evaluation of the compatibility and sustainability of hydropower projects. Various organizations and associations at international level (International Hydropower Association, ICOLD, International Energy Agency, etc.), have made significant efforts to promote and disseminate the documentation of Good Practices, contributing to the global effort of making hydropower development more sustainable.

In the following some sources of information about case-histories in the field of dams and reservoir for hydropower are briefly described.

### 6.1. INTERNATIONAL HYDROPOWER ASSOCIATION, “*The Role of Hydropower in Sustainable Development - IHA White Paper – Annex E: Good Practice Examples*”, 2003

The 2003 White Paper has been issued by the International Hydropower Association. Numerous drafts of the report have been refined through a consultation process involving a wide range of organizations, covering 27 countries.

In Chapter 8 (“*The Sustainable Development Dimension of Hydropower*”), some examples of added value created by hydropower projects are summarised:

- Conon (UK): creation of a site of special scientific interest.
- Chamuera (Switzerland): extending a local project over 75 years.
- Manapouri (New Zealand): maximizing output.
- Hoover Dam and Lake Mead (USA): popular recreational zone.
- Macagua (Venezuela): development of a nature park around a reservoir.
- Miyagase (Japan): new wetland habitat protected zones.
- Niagara Falls (Canada/USA): cohabitation of nature and hydropower.
- Shuikou (China): development of a reservoir fishery.

In Annex E (“*Good Practice Examples*”), 5 case histories are described in much more detail. They are relevant to:

- Hood River Farmers Consortium (USA): developing small-scale hydropower facilities in an irrigation district.

- Shuikou Hydroelectric Project (China): a development approach to dam-related resettlement, benefit sharing through the establishment of post resettlement and rehabilitation funds, follow up studies.
- King River Power Development (Tasmania, Australia): development and sustainable operation of a hydroelectric scheme, with predominantly environmental and economic development reasons and complementary technical innovations.
- EM-1 Hydropower Dam and EM-1-A and Rupert Diversion Project (Québec, Canada): benefit sharing between the hydropower industry and indigenous communities, involved in every step of the project, from preliminary studies to project development.
- Salto Caxias Resettlement Project (Brazil): public participation, sharing the responsibilities with the affected communities and stakeholders since the beginning of the project.

## 6.2. THE WORLD COMMISSION ON DAMS, "*Dams and Development – A new framework for decision making*", 2000

Within the context of the work carried out by the World Commission on Dams several case studies were examined, to offer an integrated look at dams from the perspective of all interest groups. The Case Studies review were contracted to lead authors, selected by the WCD for their professional expertise and independence. For each selected dam a study team and a group of stakeholders examined the following aspects: projected versus actual benefits, costs and impacts; unexpected benefits, costs and impacts; distribution of costs and benefits; decision making process; compliance with criteria and guidelines; lessons learned. The analyses of the case studies were documented in specific reports.

All terms of reference, and final draft reports, were peer-reviewed by local stakeholder groups composed of 8–10 people with varying backgrounds, regions of origin and perspectives. These reports contributed to the WCD Knowledge Base, and complemented the regional consultations, where Commissioners heard firsthand about relevant regional experience from governments, members of civil society and the private sector. These reports remained as input to the Commission rather than products of its deliberations.

The following "*Individual Dams/River Basins*" case studies were considered for hydropower development. The relevant reports are available on the WCD website (www.dams.org).

- Tucurui Dam and Amazon/Tocantins River (Brazil)
- Glomma And Lågen River Basin (Norway): an integrated system of 40 dams and reservoirs, watercourse diversions and 51 hydropower stations

– Tarbela Dam and Indus River Basin (Pakistan)
– Pak Mun Dam and Mekong/Mun River Basins (Thailand)
– Aslantas Dam and Ceyhan River Basin (Turkey)
– Grand Coulee Dam and Columbia Basin (USA)
– Kariba Dam and Zambesi River Basin (Zambia / Zimbabwe)

The way in which the case histories were examined and evaluated by the WCD was criticized by several organizations, ICOLD among them. They claimed that the WCD work did not present a proper balance between recognizing the benefits that the dams have realized as opposed to the problems they have created.

## 6.3. U.N. ENVIRONMENT PROGRAMME, DAMS AND DEVELOPMENT PROJECT, "*Comprehensive Options Assessment Of Dams And Their Alternatives - Case Studies*", 2003

The case studies presented in this document reflect more the state-of-the art than the ideal, best practices for dam project assessment. They are presented to share lessons learned, both successes and failures.

The following Case Studies are pertinent for hydropower developments:

– Wloclawek dam (Poland) - A study of a comprehensive solution to the problems of the Wloclawek dam and reservoir: anticipated social, economic and environmental effects

– BC Hydro Stave River Water Use Plan (Canada): implementation of a collaborative process to develop a water use plan for a new 90 MW hydropower facility

– Aral Sea Basin Multistate Water Resource Cooperation (Central Asia): this case study illustrates the political instruments set up to promote mutually beneficial cooperation on regional water resource management among 5 newly independent republics in the Aral Sea Basin.

– Nam Theun 2 Hydro Project (Laos)

– Karakaya dam and hydropower plant Project (Turkey)

– National Hydropower Plan Study, Vietnam: A new approach to sustainable hydropower development

## 6.4. PROCEEDINGS OF THE 23rd ICOLD CONGRESS, QUESTION 88 "Dams And Hydropower", 2009

The Question n. 88 of the 23rd ICOLD Congress (Brasilia, 2009) was relevant to "*Dams and Hydropower*". Among the pre-defined related topics, the following topics were included:

- Hydropower potential and current developments. Role in the framework of renewable energy.
- Good practices in social and environmental issues. Hydropower objectives in multipurpose reservoirs.
- Pumped storage schemes

In the submitted papers, those listed hereunder describe interesting case histories about dams for hydropower. In some cases the description of the case history is comprehensive, including various different aspects. In some cases the paper is relevant only to some aspects.

Hydropower potential and developments.

- Paper R.10 - "*Role of Large Dams And Storage Reservoirs in Hydropower Generation in Romania*": hydropower development on the Lotru river; evaluation of the benefits of the hydroelectric cascade (5 dams and reservoirs, 3 power plants, 3 pumping plants).
- Paper R.16 - "*Development of La Romaine project in Quebec* (Canada)": 4 generating stations, 1 550 MW total capacity, and conclusion of the construction in 2020.
- Paper R.11 – "*Technical Solution and Technology of Construction of Tidal Power Plants' Dams in Russia"*: reduction of construction cost by floating modules, building technology and orthogonal turbines.
- Paper R.24 – "*Additional Construction of Small Water Power Plants by Previously Built Dams*" (Czech Republic): implementation of small hydropower plants at existing water supply dams, to exploit concentrated heads and discharges.
- Paper R.25 – *"Susa Gorge: a Demodulation Reservoir for Pont Ventoux Plant (*Italy)": pumped storage, underground power station, demodulation reservoir to avoid frequent and sudden changes of the river discharges.
- Paper R.27– "*Hydroelectric Potential of Russia and its Perspectives of Use*"

Social and environmental aspects in design, construction, operation.

- Paper R.05 – "*A Multipurpose Lower Sava River Project in Slovenia*": chain of 6 run-of-the-river hydropower plants; multipurpose project; a wide range of environmental concerns was handled by constant and open communication with professional and lay public.
- Paper R.08 – "*Siting Aspects of Dasu Hydropower Project."* (Pakistan): influence of social and environmental issues (populated village, area of historic significance) on the design of the project.
- Paper R.40: "*Lower Carony River projects"* (Venezuela). Measures undertaken to bring benefits to the impacted communities and to minimize the impacts on the ecosystem in an area where large power plants are in operation.

- Paper R.14: “*Studies for the Diquis Hydroelectric Project*” (Costa Rica): seeking the environmental and social viability resulted in a new design solution for the hydroelectric development, avoiding resettlement of indigenous populations and minimizing the impact on native territories and on major ecosystems in the area.
- Paper R.17 – “*Research and Practice of Eco-Adaptability Management of the Three Gorges Project*” (China): benefits provided by the project; practices in ecological replenishment.
- Paper R.18 – “*Measures to Protect Aquatic Resources in Large-Scale Hydraulic Engineering Projects on The Yangtze River*” (China): environmental protection incorporated into the entire process, from planning to execution and operation.
- Paper R.12 – “*Niagara Power Project: a Success Story of International Cooperation*” (USA): international cooperation established priority for scenic, navigation, domestic and power generation purposes.

Pumped storage schemes

- Paper R.33 – “*Tehri Pumped Storage Plant Project*”: the challenge of the widest head range of operation worldwide (130-230 m)
- Paper R.39 – “*The Power Plant Kops II in Western Austria*”.

6.5. INTERNATIONAL ENERGY AGENCY, Implementing Agreement For Hydropower Technologies and Programmes, “*Hydropower Good Practices: Environmental Mitigation Measures And Benefits*”, May 2006.

The International Energy Agency promoted a collection of successful experiences in mitigating negative environmental impact related to hydropower development around the world, as well as specific examples showing a variety of benefits created by hydropower development.

Sixty good practice cases, worldwide, were examined. A wide diversity among the various cases was found, because the measures to mitigate negative impacts and to optimize positive outcomes are clearly project specific.

They are located in 20 different countries (about half of them in Japan) : Japan (27), Canada (9), Turkey (3), Australia (2), India (2), Norway (2), Taiwan (2), Thailand (2), Malaysia (1), USA (1), Argentina-Paraguay (1), Austria (1), Brazil (1), Finland (1), Indonesia(1), Laos (1), Philippines (1), South Africa (1), Vietnam (1).

The sixty cases described in the report are distributed throughout various topics: Water Quality (10 cases), Biological Diversity (5), Hydrological Regimes (5), Fish Migration and River Navigation (5), Landscape & Cultural Heritage (5), Development of Regional Industries (5), Resettlement (4), Benefits due to Power Generation (4), Benefits due to Dam Function (4), Reservoir Sedimentation (3), Reservoir Impoundment (2), Minority Groups (2), Public Health (2), Improvement of Infrastructure (1), Others (3).

The cases described in the report are the following:

KI-1 Biological Diversity

- Okinawa Pumped Storage PP (Japan) - ecosystem conservation measures
- Okutadami & Ohtori Expansion Project (Japan) - ecosystem conservation
- Shin-Hannou Substation (Japan) - forestation and re-vegetation of a construction site
- Tomura PP (Japan) - post-project investigation of river ecosystem recovery
- Palmiet (South Africa) - ecosystem conservation by environmental management plan

KI-2 Hydrological Regimes

- Futagawa Dam (Japan) - monitoring of river system recovery
- Tsuga Dam (Japan) - monitoring of river system recovery
- Aishihik Hydro (Canada) - water management in relation to Water License Renewal
- Churchill River Project (Canada) - weir to raise river water level & fish protection
- Ulla-Forre Project (Norway) – the best hydrological regime for hydro production and river ecology

KI-3 Fish Migration and River Navigation

- Daini Numazawa PP (Japan) - acoustic fish entrainment prevention system
- Funagira PP (Japan) - fish ladder and monitoring of fish migration
- Maan Dam (Japan) - large scale fish ladder and monitoring of fish migration
- Chambly Dam (Canada) - fish way retrofit
- Puntledge PP (Canada) - fish bypass screen at power intake

KI-4 Reservoir Sedimentation

- Dashidaira Dam (Japan) - large scale sedimentation flushing operation
- Miwa Dam (Japan) - sediment control for dam using bypass tunnel
- Cameron Highlands Scheme (Malaysia) - sediment management

KI-5 Water Quality

- Asahi Dam (Japan) - diversion of sediment and turbid water during flood
- Hydropower dams -Hida River (Japan) - selective intake and dam operation
- Kamafusa Dam (Japan) - water quality control by aeration in reservoir
- Kobo Dam (Japan) - turbid and cold water problems
- Tsukabaru Dam (Japan) - reduction of water bloom by ultraviolet irradiation
- Mingtan Pumped Storage PP (Taiwan) - water quality and ecology
- Arrow Lakes Station (Canada) - reduction of dissolved gas supersaturation
- Shasta Dam (USA) - water temperature and salmon habitat restoration
- Yacyreta Project (Argentina/Paraguay) - reduction of dissolved gas supersaturation
- King River Power Development (Australia) - water quality associated with copper mine

KI-6 Reservoir Impoundment

- Numappara Pumped Storage PP(Japan) - marshland conservation
- Sugarloaf Reservoir Project (Australia) - management of environmental and social impact

KI-7 Resettlement - rebuilding of resettled communities

- Chiew Larn Multipurpose Project (Thailand)
- Song Hinh Larn Multipurpose Project (Vietnam)
- Uri Hydroelectric Project (India)
- Salto Caxias Hydroelectric Project (Brazil)

KI-8 Minority Groups

- La Grande (Canada) - remedial measures with indigenous people
- Minashtuk Station (Canada) - partnership with indigenous community

KI-9 Public Health

- Chamera (India) - health infrastructure improvement
- LaGrande (Canada) - health issues (temporary mercury increase)

KI-10 Landscape and Cultural Heritages

- Chinda PP (Japan) - conservation of historical waterfall
- Kurobe River (Japan) - powerhouse landscape designs for six power plants
- Border Euphrates Project (Turkey) - transfer and preservation of inundated cultural heritage
- Aurland Hydropower Project (Norway) - conservation of natural and cultural landscape
- Kokkosniva HPP (Finland) - preservation of old village and river habitat

KI-11 Benefits due to Power Generation

- Integrated Hidaka River System (Japan)- power supply and regional development
- TEPCO Pumped Storage PP (Japan) - improvement in power system performance
- Mahagnao Micro-Hydro Project (Philippines) - Preservation of the natural environment
- Keban Dam and HPP (Turkey) - power supply and industrial development

KI-12 Benefits due to Dam Function

- Bhumibol Dam (Thailand) - irrigation and hydropower production
- Nam Ngum 1 HPP (Laos) - multipurpose benefits from plant built for single purpose
- Ataturk Dam and HPP (Turkey) - regional benefits from multipurpose development
- Freudenau Hydropower Plant (Austria) - groundwater management system

KI-13 Improvement of Infrastructure

- Sainte-Marguerite-3 (Canada) - measures to improve infrastructure and to foster development of regional industries

KI-14 Development of Regional Industries
- Gosho Dam (Japan) - environmental improvement & tourism development
- Kurobe No. 4 Power Plant (Japan) - tourism development at dam site
- Miyagase Dam (Japan) - tourism development at dam site
- Yasaka Dam(Japan) - environmental improvement & sightseeing
- Cirata Project (Indonesia) - reservoir fishery in resettlement program

KI-15 - Others
- Shin-Shimodaira & Shin-Koara PP (Japan) - wood wastes at dam site
- Taki Dam (Japan) - use of driftwood in reservoir
- Tomisato Dam (Japan) - recycling of felled trees at dam site

## 6.6. GOVERNMENT RUN REGIONAL DEVELOPMENT PROGRAMMES BASED ON WATER RESOURCE, Dams & Hydropower Schemes. North of Scotland Hydro Electric Board (UK).

Between 1945 and 1960 an extensive system of small and medium hydropower schemes were developed in the northern highlands of Scotland. This was primarily conceived as a social and economic development programme, with a strong focus on providing electricity to remote highland communities. Due to the importance of the fishing and hunting in the highlands, environmental issues were given a level of attention that was unusual at that time, especially in the provision of fish passes at the dams. The programme was successful in facilitating rural electrification, development and opening up opportunities for local industry and tourism, with limited environmental impact. Approximately 500,000 people per year now visit one of the hydro sites and its fish pass. Even now this development is portrayed in popular literature.

The case histories are documented in the following references:
- POWER FROM THE GLENS - ‘NEART NAN GLEANN’, Scottish & Southern Energy
- Miller, Jim “The Dam Builders: Power from the Glens “ (ISBN 1841582255; Birlinn 2003)
- Wood, Emma “The Hydro Boys: Pioneers of Renewable Energy” ( ISBN 1-84282-047-8); Luath Press, 2005
- Campbell, Patrick “Tunnel Tigers: A First-hand Account of a Hydro Boy in the Highlands” Luath Press, 2004

# 7. INFORMATION SOURCES

In this section information is given about some sources that can provide useful information and knowledge about hydropower and dams for hydropower. The sources include magazines and websites (associations, agencies, organizations), at international level. Information sources at national level are not included.

## 7.1. INTERNATIONAL HYDROPOWER ASSOCIATION – Website: www.hydropower.org

The International Hydropower Association (IHA) aims to advance sustainable hydropower's role in meeting the world's water and energy needs, by championing continuous improvement and sustainable practices, building consensus through partnerships with other stakeholders, and driving initiatives to increase the contribution of hydropower.

IHA is a non-governmental, mutual association of organisations and individuals, formed in 1995 as a forum to promote and disseminate good practice and knowledge, open to all those involved in hydropower, with members active in more than 80 countries.

IHA's policy-orientated work programme covers five themes:

- Sustainability - focusing on implementing the *Hydropower Sustainability Assessment Protocol,* supported by governments, NGOs and financial institutions including the European Commission in the form of the '*Hydro4LIFE*' project. The Protocol is the result of a multi-stakeholder development process and builds on IHA's work on this over the past decade. It's available for download at: www.hydrosustainability.org

- Climate Policy – research and outreach activities focus on hydro's role in climate mitigation and adaptation, the Greenhouse Gas (GHG) Research Project, and hydropower's vulnerability to hydrological change. The GHG Research Project was established in 2008 in collaboration with the International Hydrological Programme (IHP) of UNESCO to address questions over the status of GHG emissions from freshwater reservoirs and river basins. The Project benefits from a consensus-based, scientific approach involving collaboration and peer review from researchers, scientists and professionals from more than 100 institutions. A major milestone was achieved in 2010, with the publication of the GHG Measurement Guidelines for Freshwater Reservoirs (www.hydropower.org/climate_initiatives/GHG_Measurement_Guidelines.html)

- Energy Policy - Activities are focused on accelerating the uptake and deployment of hydropower and other renewable energy technologies.

Special emphasis is put on hydropower's synergies within the portfolio of renewables.

- Water Policy - Research and policy covers the water-energy nexus, working in collaboration with UN-Water, the World Water Council, and the Water and Climate Change Coalition. This involves the co-coordination of a Water-Energy Key Priority at the 2012 World Water Forum as well as the work within scientific networks to explore the question of energy impacts on water.

- Markets and Investment - IHA has an active working group which reviews financial models for new projects, analyses markets, including reporting on the Clean Development Mechanism, and monitors levels of hydropower deployment worldwide.

### 7.2. INTERNATIONAL ENERGY AGENCY - Website: www.iea.org

The IEA acts as energy policy advisor for its 26 member countries in their effort to ensure reliable, affordable and clean energy. Founded during the oil crisis of 1973-74, to coordinate measures in times of oil supply emergencies, IEA now focuses on broader energy issues, including climate change policies, market reform, energy technology collaboration and outreach to the rest of the world.

IEA conducts a broad programme of energy research, data compilation, publications and public dissemination of the latest energy policy analysis and recommendations on good practices.

To provide a framework for international collaboration in energy technology R&D, demonstration and information exchange, the IEA has established "*Implementing Agreements*", which specify the commitments of the Contracting Parties and provide for the production and protection of intellectual property, and record arrangements for commercial exploitation and benefit sharing.

The *Hydropower Implementing Agreement* (website: www.ieahydro.org) is a working group aimed to promote the development of new hydropower and the modernisation of existing hydropower, encouraging and supporting the sustainable development and management of hydropower. The participating countries are: Brazil, Canada, China, Finland, France, Japan and Norway.

On the web site information about current activities, details of past achievements, reports to download and hydropower news can be found.

The current main activities are the following:

- "*Small-Scale Hydropower*": a task force runs an international database (International Small–Hydro Atlas, website: www.small-hydro.com), which facilitates the development of small hydro projects, providing assessment tools, country profiles, international contacts, etc.
- "*Hydropower Good Practices*": a task force was formed to document

successful mitigation measures in the design and operation of hydropower projects. The report "*Hydropower Good Practices: Environmental Mitigation Measures and Benefits*", published in 2006, documented sixty extensively case histories collected from 20 countries (see Chapter 6).

- "*Wind/Hydro Integration*", to investigate the integration of wind and hydropower and to undertake studies on related issues.

## 7.3. EUROPEAN SMALL HYDRO ASSOCIATION - Website: www.esha.be

The European Small Hydropower Association (ESHA) is a lobby organization established in 1989 for promoting the interest of small hydropower plants (SHP, <10 MW) by informing and lobbying decision-makers at European institutions, national governments and local authorities on crucial issues facing the small hydropower sector.

ESHA activities are therefore aimed to:

- Guarantee the representation of the sector at EU level
- Improve the market conditions of the SHP industry
- Increase the electricity production from SHP
- Facilitate the removal of any barriers to SHP development in the EU

To this aims ESHA uses synergies at the European-national-local level, and serves to create a forum for those involved in the field of SHP and to represent their interests at European level.

ESHA is structured as a federation of EU national hydropower associations and is open to members from all sectors involved in small hydropower (equipment manufacturers, public utilities, producers, consultants, etc.).

Activities carried out by EHSA also include:

- Participation in International projects, working groups, workshops and conferences.
- Studies, Reports, Newsletter, website, Blog, to enhance dialogue among different stakeholders.
- Enhancing global co-operation with institutions outside of Europe.
- Organizing conferences, seminars, workshops

## 7.4. WORLD ENERGY COUNCIL - Website: www.worldenergy.org

Founded in 1923, the World Energy Council (WEC) is a forum for thought-leadership and tangible engagement committed to a sustainable energy future. Its mission is: "to promote the sustainable supply and use of energy for the greatest benefit of all". The WEC network consists of nearly 100 national committees, including most of the largest energy-producing and energy consuming countries, and represents over 3000 member organizations including governments, industry and expert institutions.

The work of the organization spans the entire energy spectrum (coal, oil, natural gas, nuclear, hydro and new renewables) and focuses on such topical areas as market restructuring; energy efficiency; energy and the environment; financing energy systems; energy pricing and subsidies; energy poverty; ethics; benchmarking and standards; use of new technologies; and energy issues in developed, transitional, developing countries.

WEC offers a wide variety of services, programmes and activities, and is well received on the global energy scene for its reports, analyses, research, case studies, medium and long-term energy projections, and policy and strategy recommendations.

The WEC's six main Activity Areas address long-term visionary "*Strategic Insights*" and immediate outcome-oriented "*Global and Regional Agendas*" of a collaborative nature. These activities are supported by cross-cutting "*Knowledge Networks*".

## 7.5. THE INTERNATIONAL JOURNAL ON HYDROPOWER AND DAMS (website: www.hydropower-dams.com)

The *International Journal on Hydropower & Dams* ("*H&D*") is a magazine aiming to help advance the state-of-the-art of dam engineering and hydropower development.

An Editorial Board helps to steer the policy and content of the Journal. Editorial comments are contributed each year by the Presidents of international professional associations such as ICOLD, ICID, IWRA and others.

Each Issue of the magazine has a regional focus, presenting examples of policy as well as current and planned schemes in the various regions of the world with major activities underway.

Technical themes cover a broad range of disciplines, combining state-of-the-art research and technology, practical papers on civil, mechanical and electrical engineering topics, as well as policy papers. Emphasis is on best practice, in terms of safety, economy, and responsible planning.

Yearly, a European "HYDRO" Conference and Exhibition is organized by H&D, to discuss hydro development programs, priorities, achievements and challenges. This event is also taken to Asia in alternate years.

Other specific features of H&D are the following:

– "*World ATLAS*": annual world survey of hydropower developments, including statistical data on hydro potential, dams under construction, roller compacted concrete dams, concrete faced rockfill dams, dams with asphaltic facings or cores.

– "*Organization Database*", listing many national and international organizations involved in water resources development.

– “*Industry Guide*”, containing more than 1000 companies active in the dams and hydropower industry.

– “*Maps*”: world maps are published each year they show major schemes under construction (dams higher than 60 m), the total numbers of dams in each country, information on hydropower capacity and production.

– “*Technical Posters*”, generally produced to commemorate major international conferences, including those held by ICOLD.

## 7.6. HYDRO REVIEW WORLDWIDE – Website: www.hydroworld.com

The *Hydro Review Worldwide* (HRW) is a bimonthly magazine, having the mission to give a comprehensive coverage of the hydroelectric industry worldwide, and provide the sector community with a worldwide network for sharing practical, technical information and expertise on hydroelectric power.

This community includes:

– Developers, owners, and operators of hydroelectric plants and dams.
– Service providers, engineering and environmental consultants.
– Equipment vendors.
– Regulators, financiers, and legal specialists.

HRW is aimed to create opportunities for doing business by informing industry participants about new ideas and trends, and about available products and services. A goal is to enable project developers, owners, and operators to apply technologies more economically and effectively.

## 7.7. INTERNATIONAL WATER POWER & DAM CONSTRUCTION –Website: www.waterpowermagazine.com

International Water Power and Dam Construction magazine (IWP&DC) is an independent monthly international publication bringing up-to-date information on hydro power and dam projects from around the world.

Launched in 1949, IWP&DC provides coverage of all aspects of the hydropower and dam construction industries, including transmission and distribution technology.

Topics regularly covered include: construction, flood management, refurbishment, small hydro, operation and maintenance, licensing, project finance, turbines and generators, pumped storage technology, tunnelling and dam safety

IWP&DC has over 1000 paying subscribers and a print circulation of over 4000.It also produced as a fully interactive digital issue which is sent by e-mail link to an additional audience of some 12 000 readers

As well as the monthly journal, IWP&DC also publishes an annual yearbook, featuring statistical information on dams and hydro plants worldwide, information on recent equipment contracts, an in-depth project profile section, and an industry's comprehensive buyer's guide. IWP&DC also produces a free weekly email newsletter.

The accompanying website is packed with latest business news, fully searchable archived technical articles dating back to 1998, technology reviews, contracts, tenders, and a fully searchable Buyers Guide with over 2 500 individual company listings.

## 7.8. RENEWABLE ENERGY POLICY NETWORK – Website: www.ren21.net

The Renewable Energy Policy Network REN21 is an organization promoting a global transition to renewable energy in both industrialized and developing countries. To this aim REN21 encourages action in three areas: Policy, Advocacy, and Exchange.

- *Policy*: encouraging political support for the strengthening of regulatory environments and market structures that lead to accelerating the use of renewable energy
- *Advocacy*: advocating the deployment of renewable energy as a critical component of strategies to increase access to energy services and to alleviate poverty, by hosting high profile international events, and by producing authoritative and influential issue papers.
- *Exchange*: promoting knowledge generation and exchange by providing links among knowledge bases on renewable energy market and policy developments.

REN21's flagship publication, the annual Renewables Global Status Report (started in 2006) provides an integrated perspective on the global renewable energy situation and on renewable energy policies and market developments, serving a wide range of audiences from investors and government decision makers to students, project developers, researchers, and industrial manufacturers. It is the product of an international team of over 150 researchers, contributors, and reviewers

## 7.9. CEATI - Website : www.ceati.com

The Centre for Energy Advancement through Technological Innovation (CEATI) is a user-driven organization committed to providing technology solutions to its electrical utility participants, who are brought together to collaborate and act jointly to advance the industry through the sharing and developing of practical and applicable knowledge.

CEATI's efforts are driven by over 100 participating organizations (electric & gas utilities, governmental agencies, provincial and state research bodies), represented within 15 focused Interest Groups and specialized taskforces. CEATI's participants represent over 14 countries on 4 continents, a diversity that contributes to the strength of CEATI programs.

In addition to facilitating information exchange through topic-driven interest groups and industry conferences, CEATI brings partners together to collaborate on technical projects with a strong practical focus, and develops customized software and training solutions to fit its clients' needs.

CEATI International currently maintains 5 Interest Groups in the Electrical Generation Area, and the following 4 are linked to dams and hydroelectric plants and production:

- Dam Safety Interest Group
- Hydraulic Plant Life Interest Group
- Water Management Interest Group
- Strategic Options for Sustainable Power Generation Interest Group

## 7.10. INTERNATIONAL RENEWABLE ENERGY ALLIANCE – Website: www.ren-alliance.org

International Renewable Energy Alliance (REN Alliance) is a formal partnership by the following non-profit international organisations, representing the hydro, geothermal, solar, and wind power/energy and bio-energy sector:

- International Hydropower Association (IHA), since 2004
- International Solar Energy Society (ISES), since 2004
- International Geothermal Association (IGA), since 2004
- World Wind Energy Association (WWEA), since 2004
- World Bio-energy Association (WBA), since 2009

The alliance is aimed to provide a unified voice on renewable energy in international and regional energy media.

## 7.11. INTERNATIONAL ASSOCIATION FOR IMPACT ASSESSMENT - Website: www.iaia.org

The International Association for Impact Assessment (IAIA) is a forum for advancing innovation, development, and communication of best practice in impact assessment.

IAIA was organized in 1980 to bring together researchers, practitioners, and users of various types of impact assessment from all parts of the world. Its international membership (more than 1600 members representing more than 120 countries) promotes development of local and global capacity for the application of environmental, social, health and other forms of assessment in which science and public participation provide a foundation for equitable and sustainable development.

International conferences are held annually by IAIA. Regional conferences are also organized to make information exchange and networking opportunities available to those who might not be able to attend the international conferences, as well as to focus attention to specific issues.

Books, Special Publications, Guidelines and Principle Documents are available at the IAIA's website

Several "Sections" are managed by IAIA, to share experiences and discuss ideas, each section having its own online forum for networking, communication and posting resources. As an example, current Sections include the following: "*Agriculture, Forestry and Fisheries", "Biodiversity and Ecology", "Impact Assessment Law, Policies and Practice" , "Public Participation", "Social Impact Assessment", "Health", "Indigenous Peoples", "Energy"*, etc.

## 7.12. SECRÉTARIAT INTERNATIONAL FRANCOPHONE EN ÉVALUATION ENVIRONNEMENTALE - Website: www.sifee.org

The "*Secrétariat Int. Francophone En Évaluation Environnementale*", (SIFÉE), is a non-profit nongovernmental organization, grouping numerous organizations of French-speaking countries focused on the environmental assessment. It is supported by the governments of France, Canada and Quebec, and notably by the "*Institut de l'Énergie et de l'Environnement (IEPF)*".

Currently SIFÉE is a federation of 55 different organizations: 20 associations, 14 companies, 11 Universities or Research Centres, 10 governmental organizations.

The main mission of the SIFÉE is the promotion of the environmental assessment in all the French-speaking countries. To this aim SIFÉE promotes actions to strengthen the competence of the specialists and decision-makers involved in the field of the environmental assessment, public participation, sustainable development, favouring the exchange of experience and the link with other international organizations.

The activities carried out by SIFÉE include a yearly international seminar ("*Colloque*"), a summer school, workshops and educational and training documents. The proceedings of the "*Colloques*" and the educational and training documents are available at the SIFÉE's website.

## 7.13. EQUATOR PRINCIPLES – Website: www.equator-principles.com

The Equator Principles (EPs) are a credit risk management framework for determining, assessing and managing environmental and social risk in project finance transactions. The EPs are adopted voluntarily by financial institutions and are applied where total project capital costs exceed US$10 million. The EPs are primarily intended to provide a minimum standard for due diligence to support responsible risk decision-making.

The EPs are based on the IFC "P*erformance Standards*" and on the World Bank Group "*Environmental, Health, and Safety Guidelines*".

Equator Principles Financial Institutions (EPFIs) commit to not providing loans to projects where the borrower will not or is unable to comply with their respective social and environmental policies and procedures that implement the EPs. In addition, while the EPs are not intended to be applied retroactively, EPFIs will apply them to all project financings covering expansion or upgrade of an existing facility where changes in scale or scope may create significant environmental and/or social impacts.

## 7.14. INTERNATIONAL FINANCE CORPORATION (IFC), "*Performance Standards*" – Website: www.ifc.org

IFC's *Performance Standards* define clients' roles and responsibilities for managing their projects and the requirements for receiving and retaining IFC support. The standards include requirements to disclose information.

The Guidance Notes are companion documents to IFC's Performance Standards and provide additional guidance in fulfilling roles and responsibilities under the standards.

IFC applies the Performance Standards to manage social and environmental risks and impacts and to enhance development opportunities in its private sector financing. The Performance Standards may also be applied by other financial institutions electing to apply them to projects in emerging markets.

The following eight Performance Standards (PS) are the criteria which the client must meet throughout the life of an investment by IFC or other relevant financial institution:

- PS 1: Social and Environmental Assessment and Management System
- PS 2: Labour and Working Conditions
- PS 3: Pollution Prevention and Abatement
- PS 4: Community Health, Safety and Security
- PS 5: Land Acquisition and Involuntary Resettlement
- PS 6: Biodiversity Conservation and Sustainable Natural Resource Management
- PS 7: Indigenous Peoples
- PS 8: Cultural Heritage

## 7.15. WORLD BANK Group, "*Environmental, Health, and Safety Guidelines*"

The *Environmental, Health, and Safety Guidelines* (known as the "EHS Guidelines") are technical reference documents with general and industry-specific examples of Good International Industry Practice.

These EHS Guidelines are designed to be used together with the relevant

Industry Sector EHS Guidelines which provide guidance to users on EHS issues in specific industry sectors. For complex projects, use of multiple industry-sector guidelines may be necessary. A complete list of industry-sector guidelines can be found at: www.ifc.org/ifcext/enviro.nsf/Content/EnvironmentalGuidelines.

The EHS Guidelines are organized in the following main sections:

1. Environmental
2. Occupational Health and Safety
3. Community Health and Safety
4. Construction and Decommissioning

## 7.16. WORLD BANK, "*Environmental and social safeguard policies*"

The World Bank's environmental and social safeguard policies are a cornerstone of its support to sustainable poverty reduction. The objective of these policies is to prevent and mitigate undue harm to people and their environment in the development process. These policies provide guidelines for bank and borrower staffs in the identification, preparation, and implementation of programs and projects. The effectiveness and development impact of projects and programs supported by the Bank has substantially increased as a result of attention to these policies.

Safeguard policies have often provided a platform for the participation of stakeholders in project design, and have been an important instrument for building ownership among local populations.

The ten safeguard policies cover:

- Natural Habitats
- Forests
- Pest Management
- Physical Cultural Resources
- Involuntary Resettlement
- Indigenous Peoples
- Safety of Dams
- International Waterways
- Disputed Areas

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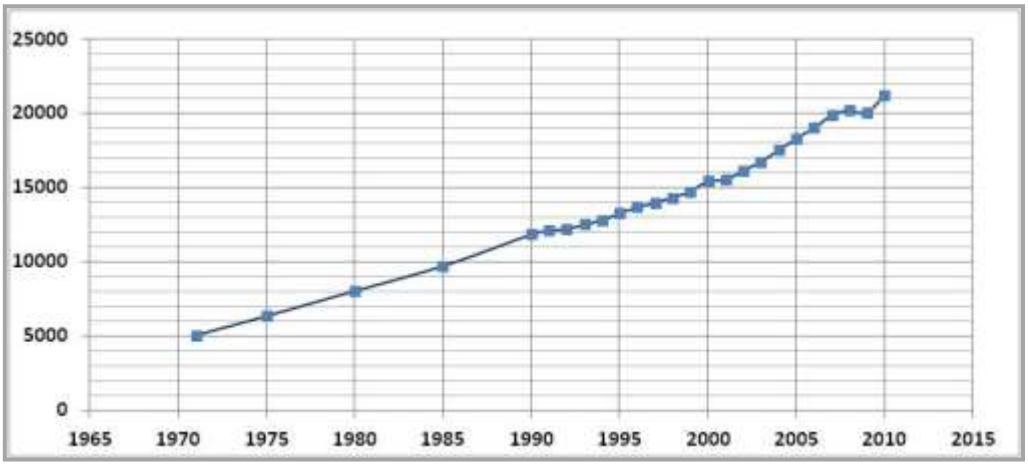



Fig. 1: Electricity production in the world (TWh) – (data from Ref. 1)

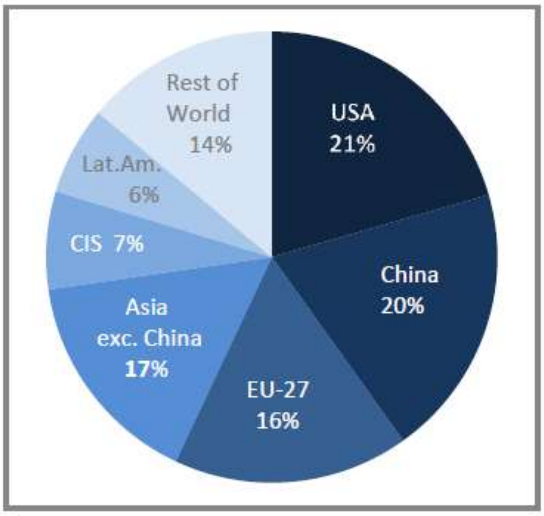
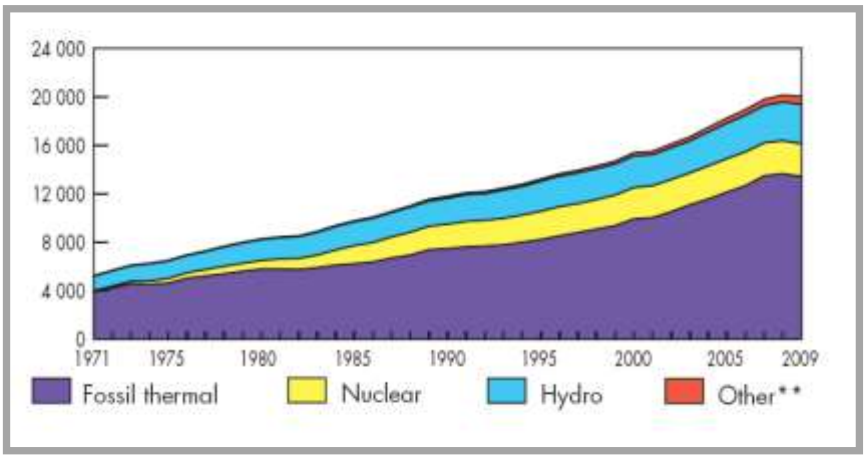
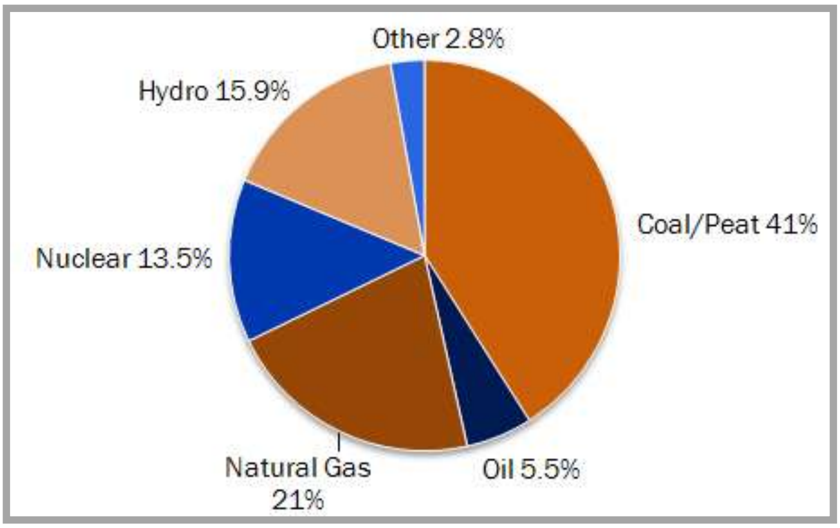



Fig. 2: Distribution of electricity generation, by region - (data from Ref. 1)




(Note: "*Other*" includes geothermal, solar, wind, combustible renewables & waste, and heat)

Fig. 3: Electricity production by fuel (TWh) - (from Ref. 3)




(Note: "*Other*" includes geothermal, solar, wind, combustible renewables & waste, and heat)

Fig. 4: Current world power generation mix - (from Ref.2)

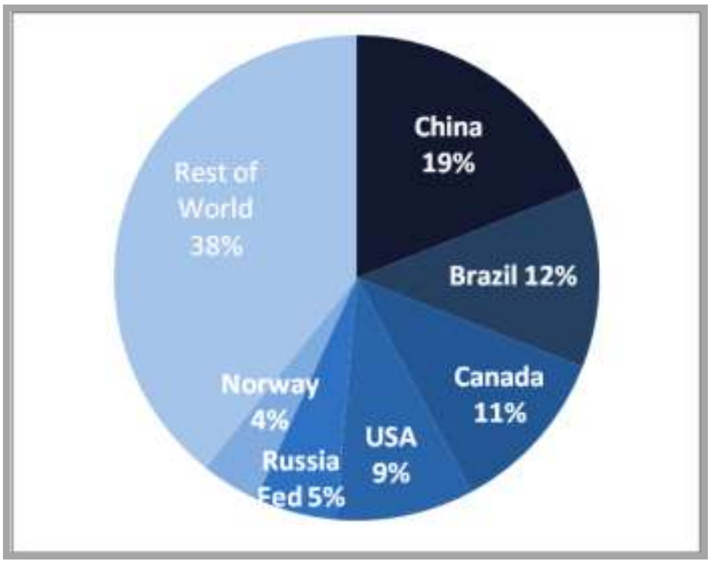



Fig. 5: Hydro electricity production, by region - (data from Ref. 3)

*Nurek dam*

*Xiaowan dam*

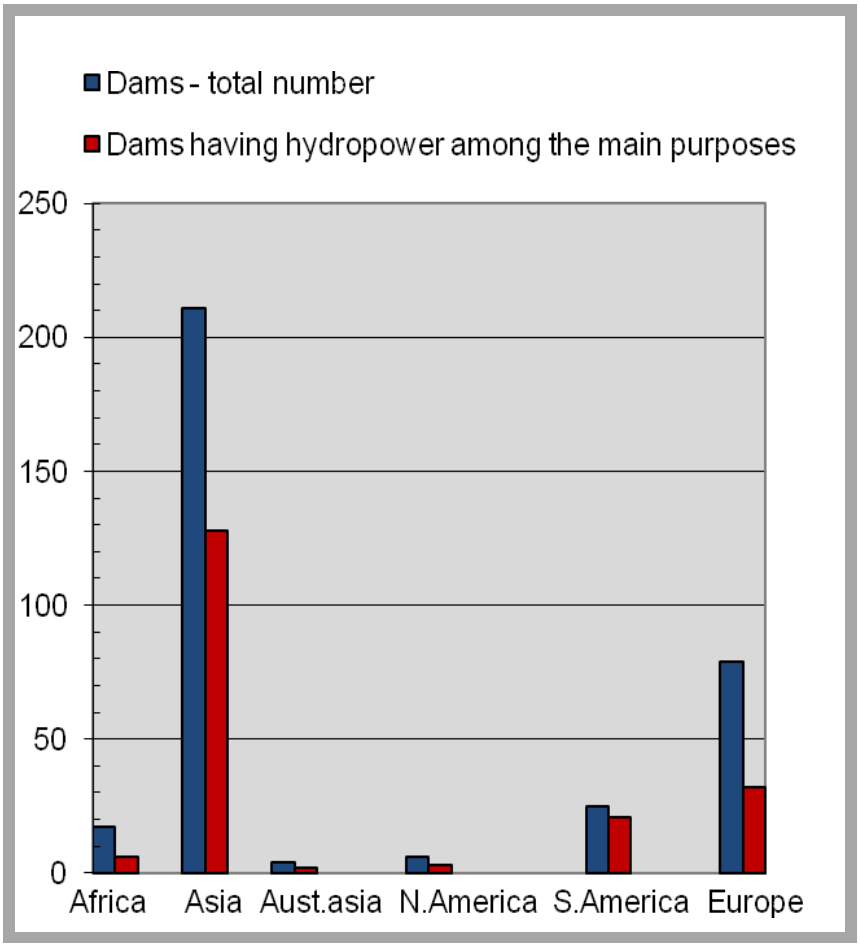
*Grande Dixence dam*

*Inguri dam*

*Chicoasén dam*

*Tehri dam*

Fig. 6: Pictures of the highest dams




NOTES:

- more than half of the dams given for “Asia” are in China + Iran
- more than half of the dams given for “Europe” are in Turkey

Fig. 7: Major dams under construction (H > 60m)

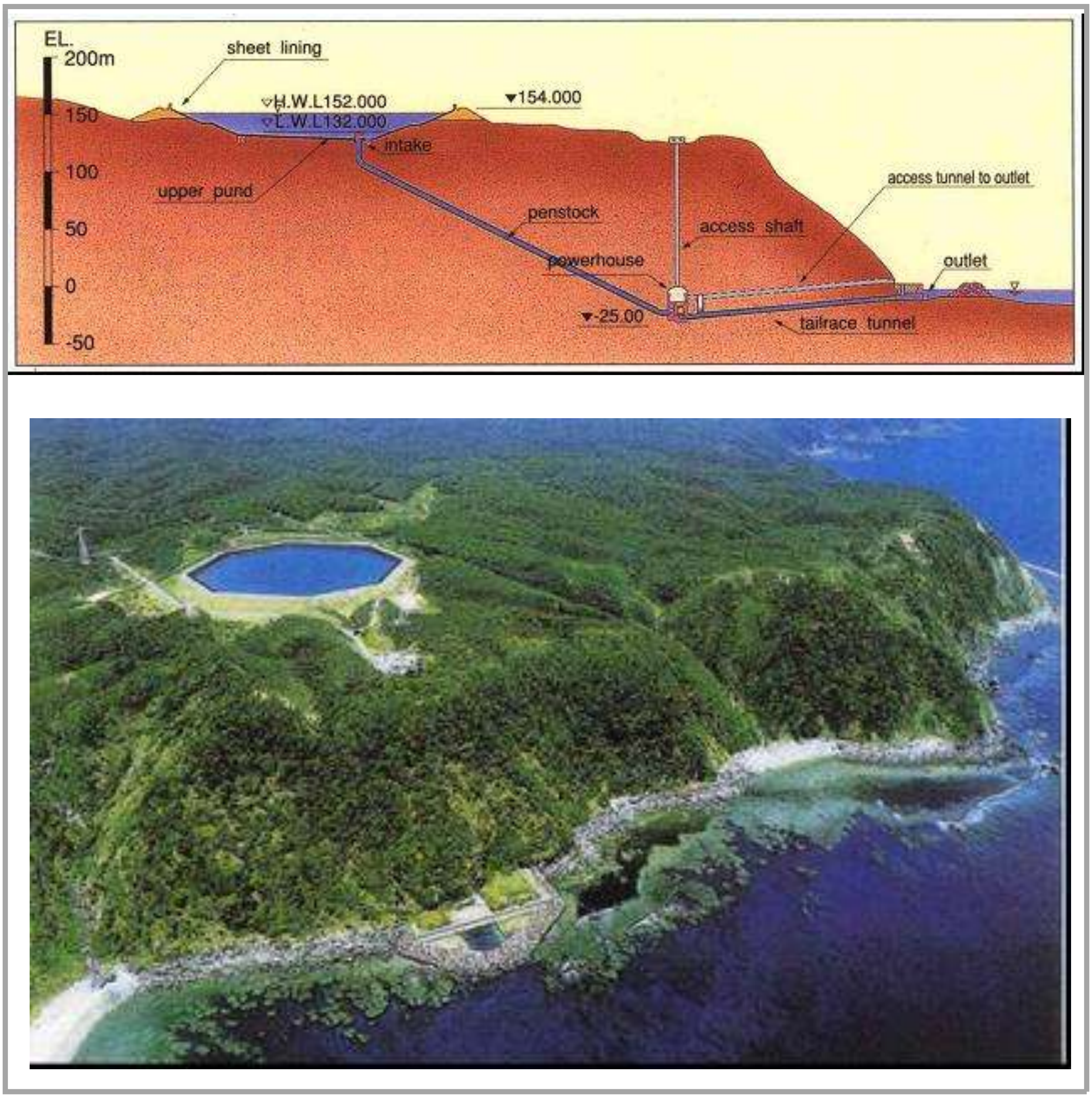
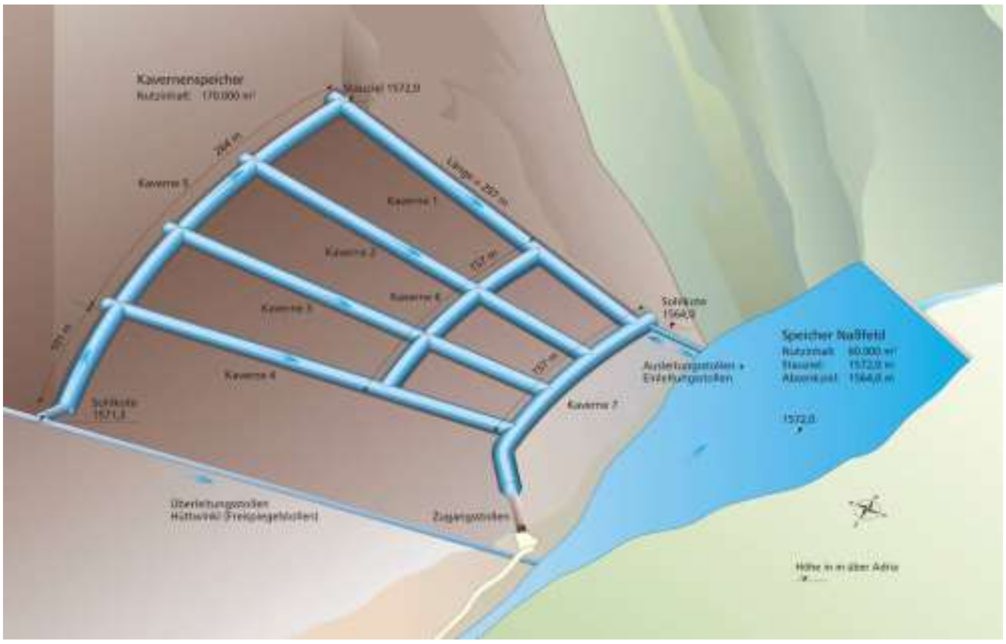



Fig. 8: Kunigami seawater pumped storage plants




*Final cavern solution.*

*Construction of the storage caverns*

*The only remaining visible cavern structure: the access tunnel portal*

Fig. 9: Underground storage - Nassfeld pumped storage plants

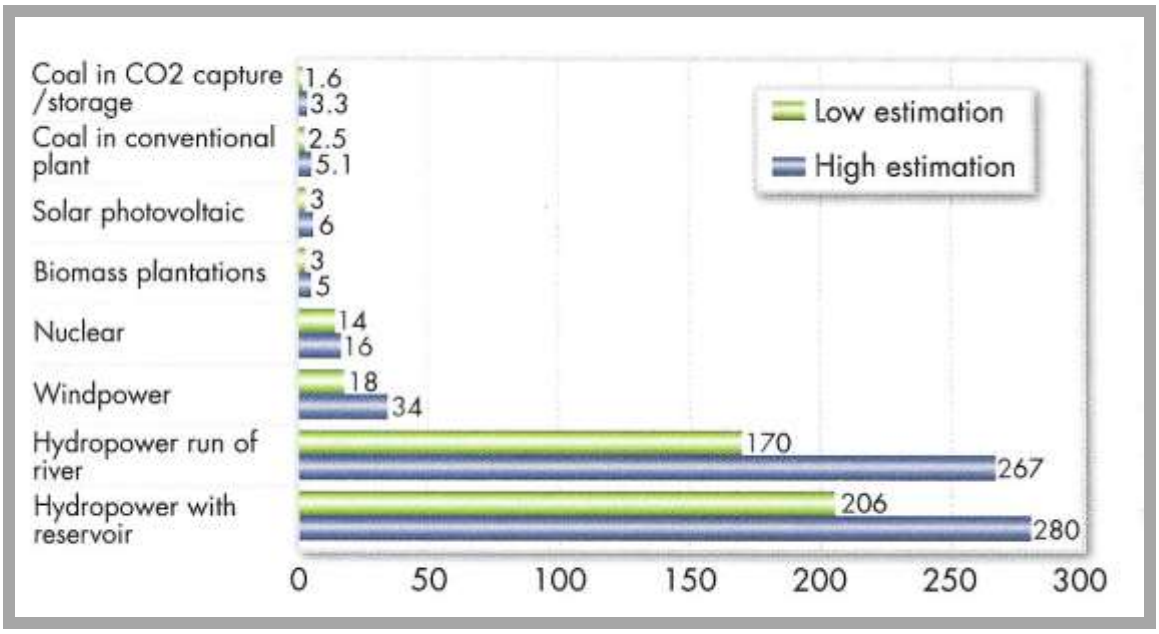
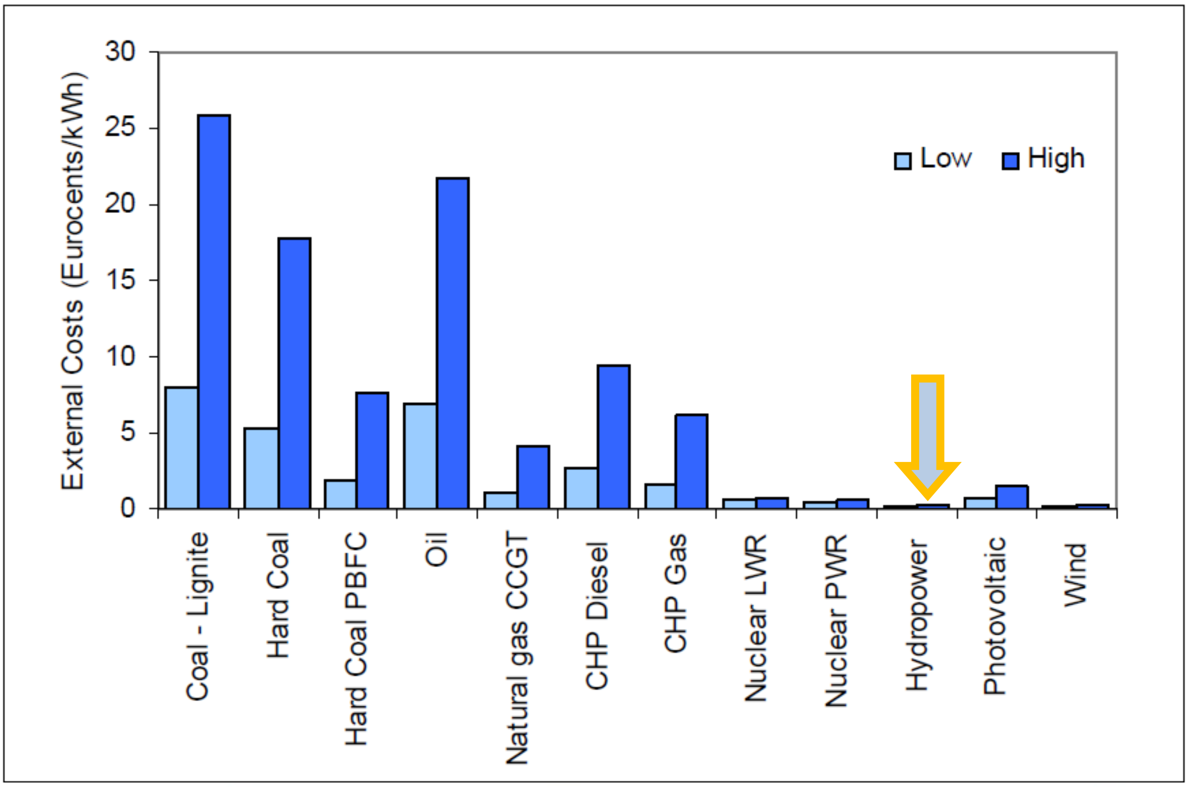



Fig.10: Energy pay back ratio - Comparison among different options (from Ref. 43)

**Table 1. Status of Renewables Technologies, Characteristics and Costs**

| Technology | Typical Characteristics | Typical Energy Costs (U.S. cents/kilowatt-hour unless indicated otherwise) |
|---|---|---|
| **Power Generation** | | |
| Large hydro | *Plant size:* 10 megawatts (MW)–18,000 MW | 3–5 |
| Small hydro | *Plant size:* 1–10 MW | 5–12 |
| On-shore wind | *Turbine size:* 1.5–3.5 MW<br>*Blade diameter:* 60–100 meters | 5–9 |
| Off shore wind | *Turbine size:* 1.5–5 MW<br>*Blade diameter:* 70–125 meters | 10–14 |
| Biomass power | *Plant size:* 1–20 MW | 5–12 |
| Geothermal power | *Plant size:* 1–100 MW;<br>*Types:* binary, single- and double-flash, natural steam | 4–7 |
| Solar PV (module) | *Cell type and efficiency:* crystalline 12–18%; thin film 7–10% | — |
| Rooftop solar PV | *Peak capacity:* 2–5 kilowatts-peak | 20–50 |
| Utility-scale solar PV | *Peak capacity:* 200 kW to 100 MW | 15–30 |
| Concentrating solar thermal power (CSP) | *Plant size:* 50–500 MW (trough), 10–20 MW (tower); *Types:* trough, tower, dish | 14–18 (trough) |

Fig. 11: Energy renewable technologies - Generating costs (from Ref. 31)




**Note**: PBFC = pressurised fluidised bed combustion, CHP = combined heat and power, CCGT = combined cycle gas turbine, LWR = light water reactor, PWR = pressurised water reactor.

Fig. 12: Estimated EU external costs for electricity generation technologies in 2005 (from Ref. 12)

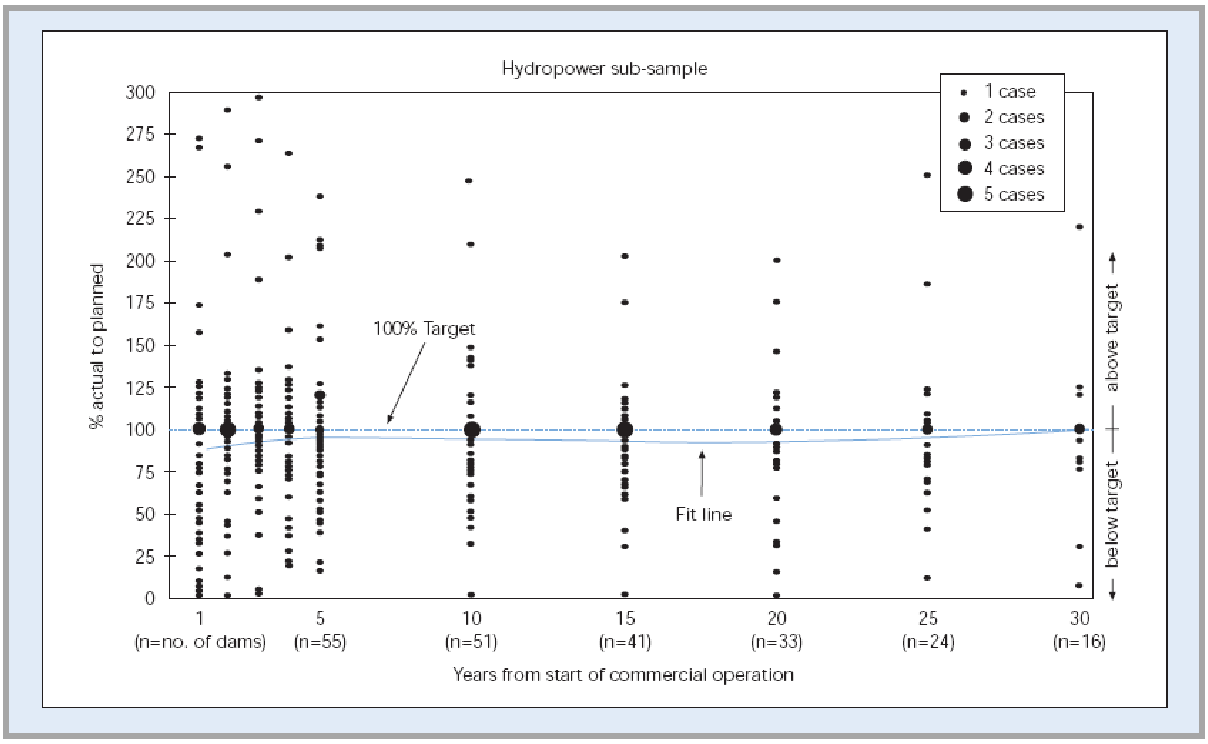



Fig. 13: Actual vs. planned hydropower generation (from Ref. 4)

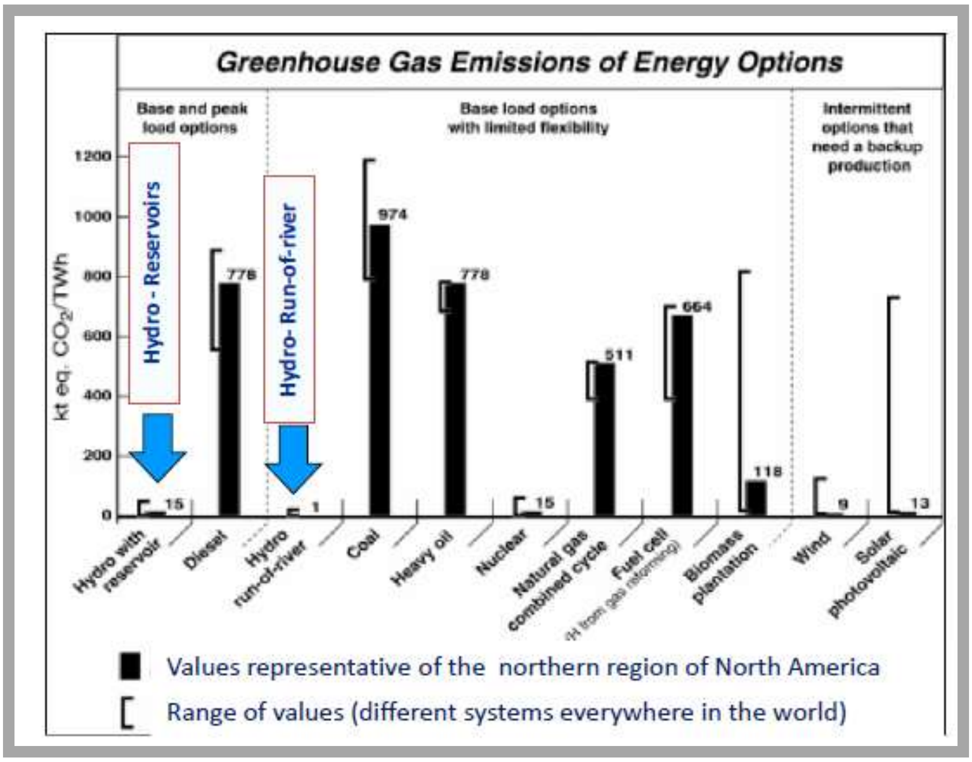



Fig. 14: GHG emissions - Comparison among power generation options (from Ref. 10)

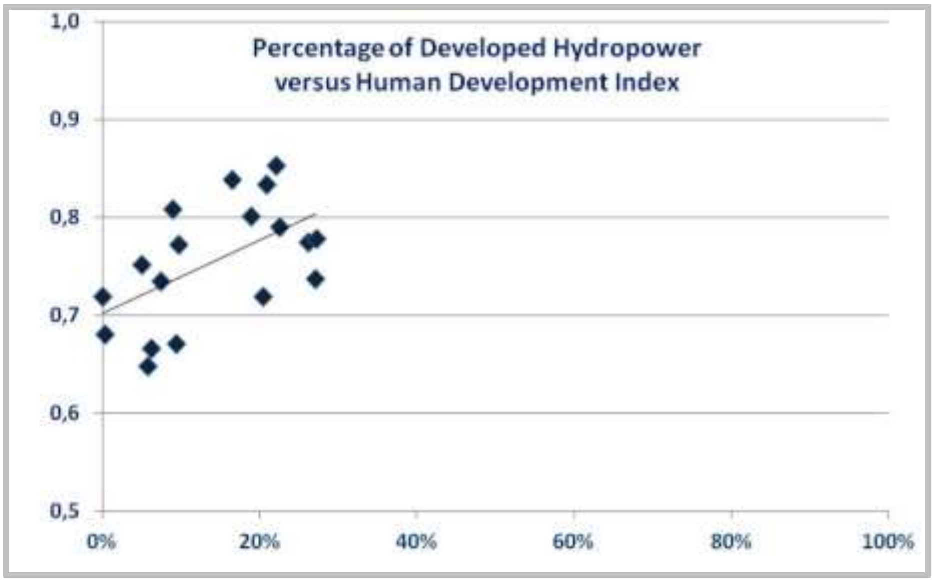



Fig.15 - Hydropower Development and Human Development Index, in South American Countries (data from Ref. 47)

NOTE: *Paraguay not included in the correlation because the existence of Itaipu, whose energy is mostly destined to Brazil, would distort its position. Uruguay also not considered because it has developed almost its whole potential as compared with less than 30% for all other countries*.

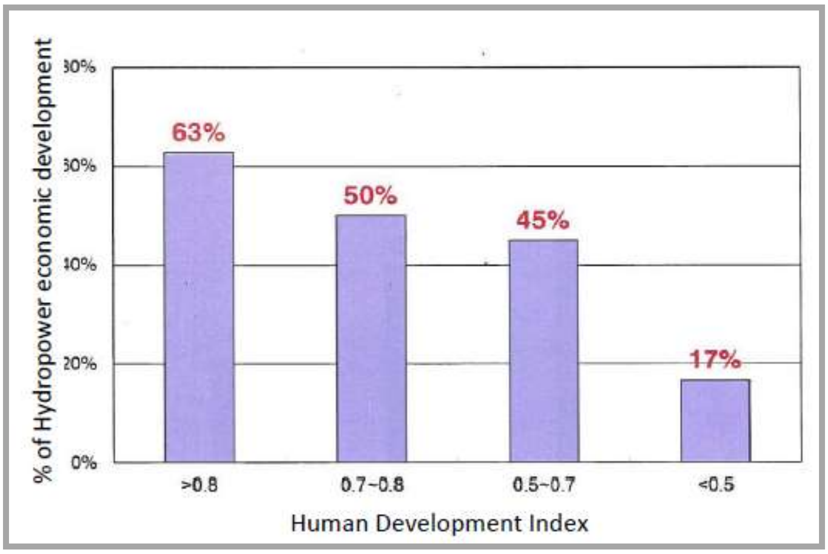



Fig. 16 - Hydropower Development and Human Development Index (from Ref. 52)

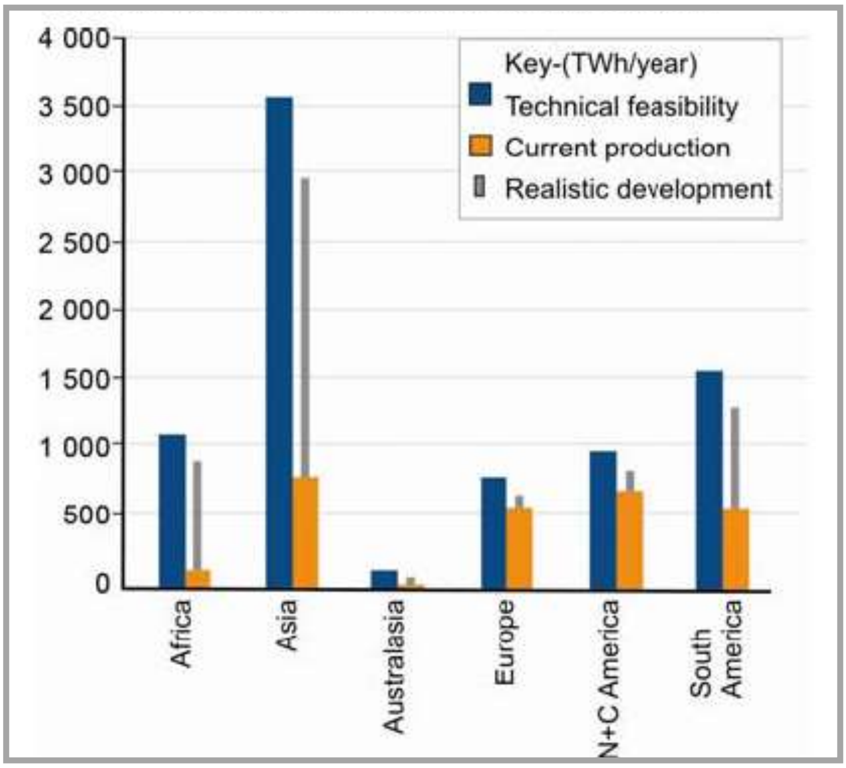



Fig. 17: Hydropower potential – Feasible vs. Exploited (from Ref. 10)

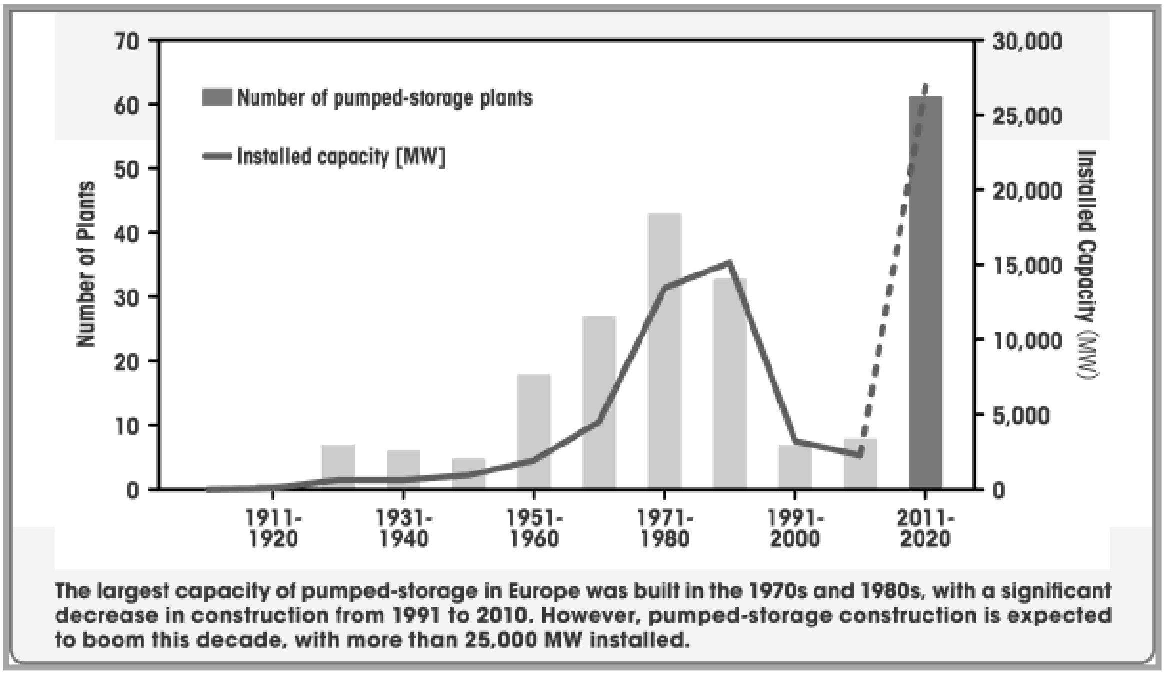



Fig. 18: Pumped Storage Construction in Europe, by decades (from Ref. 49)

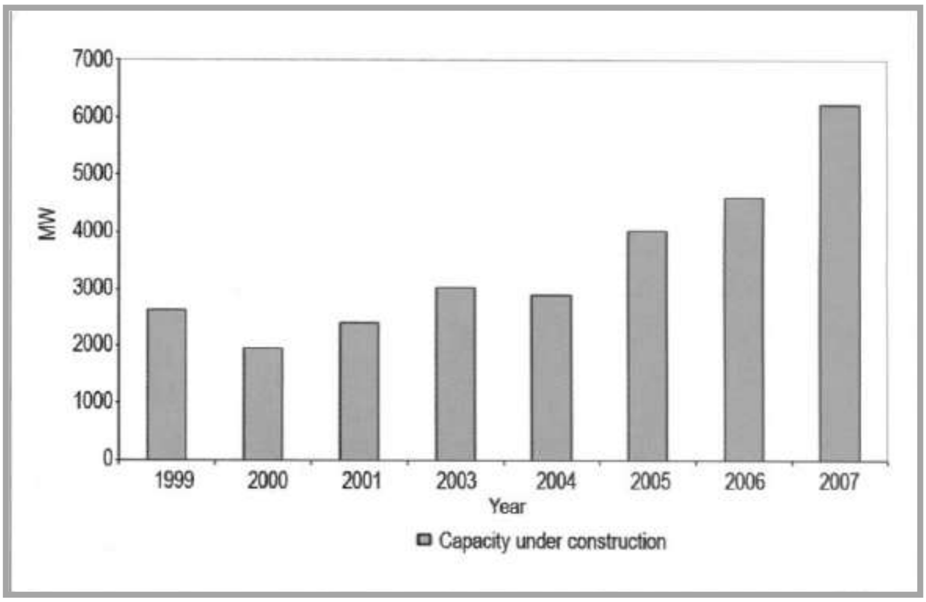



Fig. 19: Trend in hydropower construction in Africa (from Ref. 24)

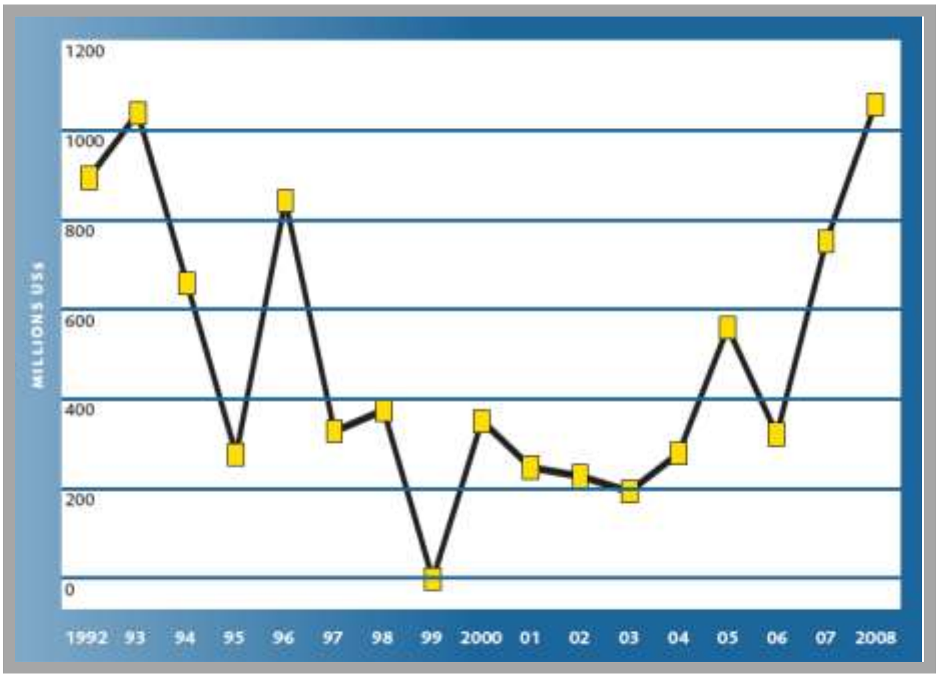



Fig. 20: World Bank lending for hydropower (from Ref. 25)

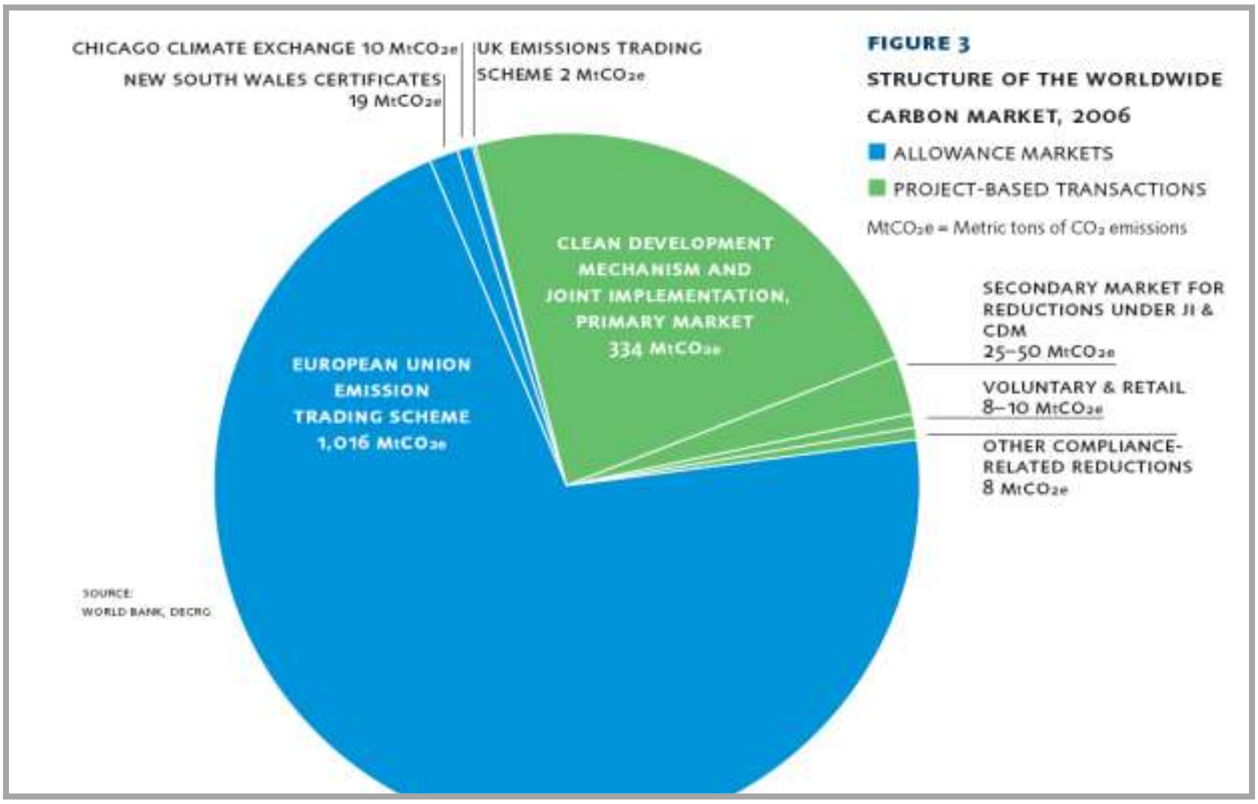



Fig 21: Worldwide Carbon Market (from Ref. 33)

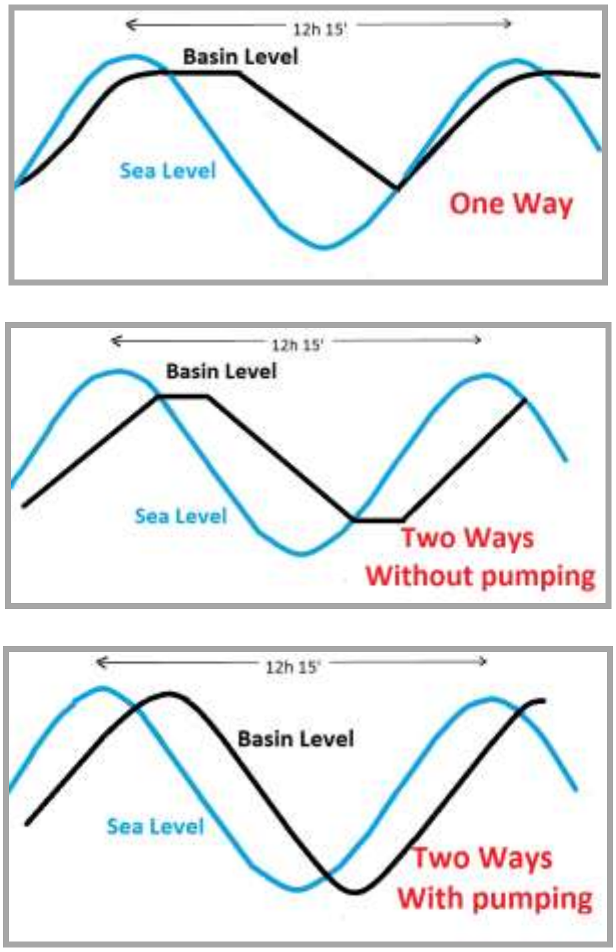



Fig. 22: Tidal power plant – Operating schemes (from Ref. 37)

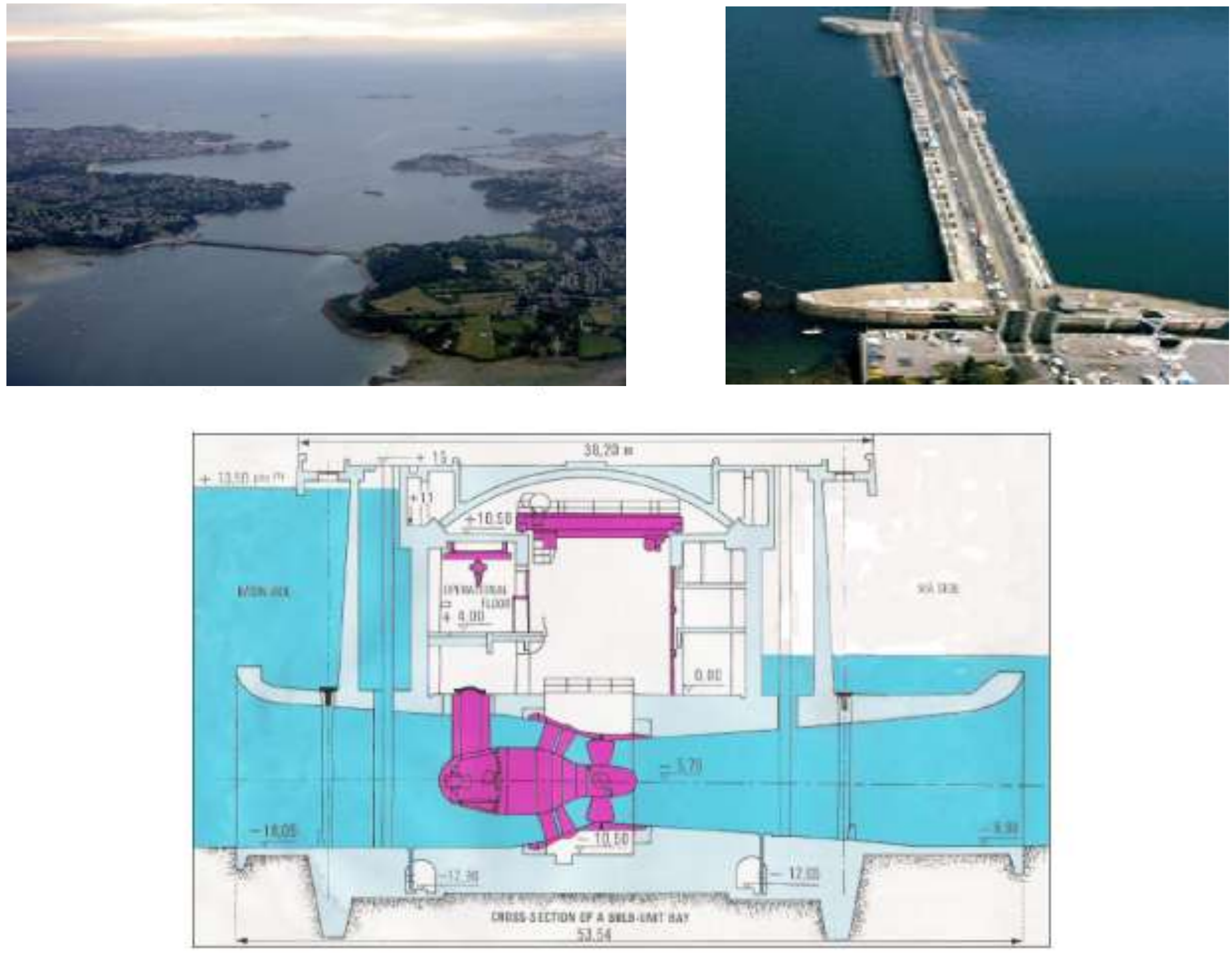



Fig. 23: The Rance Tidal Power Plant

Fig. 24: The Sihwa Lake Tidal Power Station (from Ref. 54)

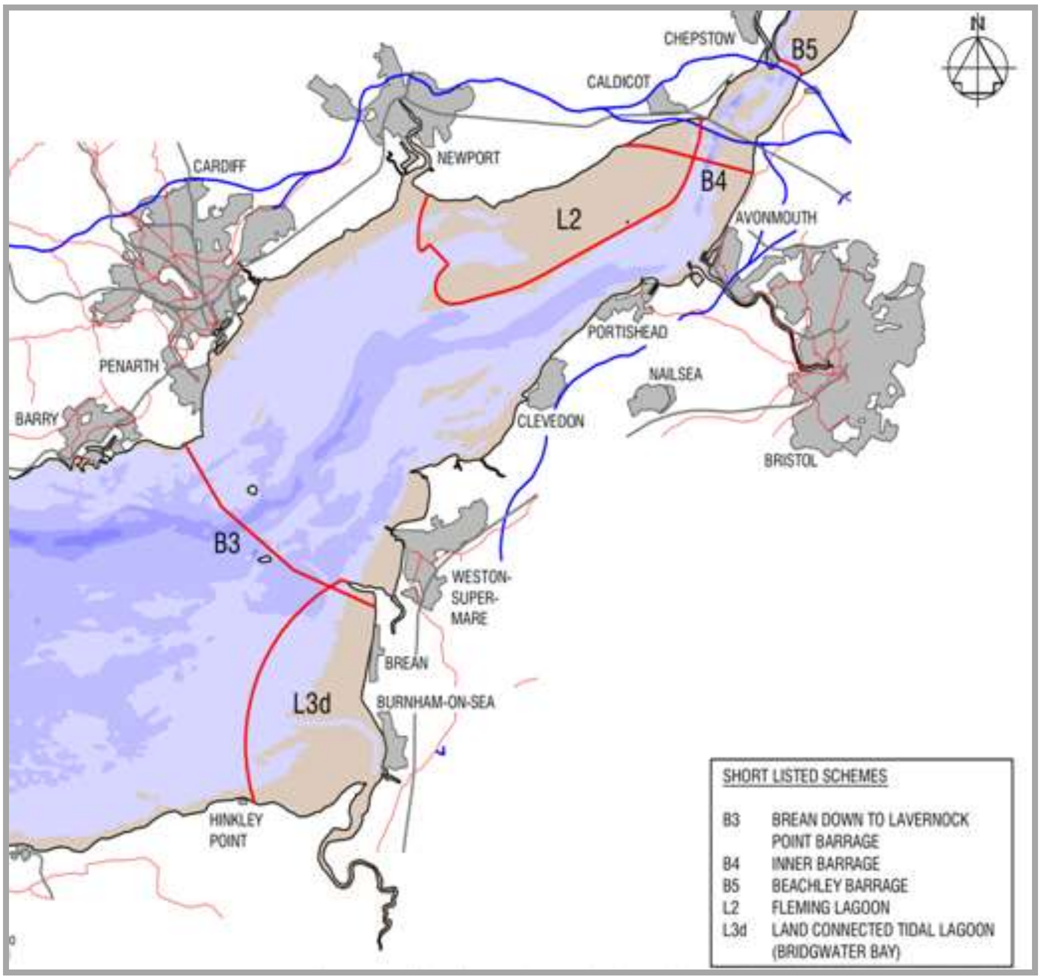



Fig. 25: The Severn barrage: options considered affordable and feasible (from Ref. 44)