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INTERGOVERNMENTAL PANEL ON climate change

Chapter 5

Hydropower

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References of figures are often missing; references from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

All monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to US$ for the base year 2005.

Chapter 5 : Hydropower

CONTENTS

EXECUTIVE SUMMARY

Hydropower is a renewable energy source where power is derived from the energy of moving water from higher to lower elevations. It is a proven, mature, predictable and price competitive technology. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire). It also has the highest energy payback ratio. Hydropower requires relatively high initial investment, but has the advantage of very low operation costs and a long lifespan. Life-cycle costs are deemed low.

The total worldwide technically feasible potential for hydropower generation is 14,368 TWh with a corresponding estimated total capacity potential of 3,838 GW; five times the current installed capacity. Undeveloped capacity ranges from about 70 percent in Europe and North America to 95 percent in Africa indicating large opportunities for hydropower development worldwide. The resource potential for hydropower could change due to a changing climate. Global effects on existing hydropower systems will however probably be small, even if individual countries and regions could have significant changes in positive or negative direction.

Hydropower has been a catalyst for economic and social development of several countries. According to the World Bank, large hydropower projects can have important multiplier effects creating an additional 40-100 cents of indirect benefits for every dollar of value generated. Hydropower can serve both in large centralized and small isolated grids. Nearly two billion people in rural areas of developing countries do not have electricity. Small hydro can easily be implemented and integrated into local ecosystems and might be one of the best options for rural electrification for instance in isolated grids, while large urban areas and industrial scale grids need the flexibility and reliability of large hydro.

Hydropower is available in a broad range of projects scales and types. Projects are usually designed to suit particular needs and specific site conditions. Those can be classified by project type, head, purpose and size (installed capacity). Size wise categories are different worldwide due to varying development policies in different countries. The hydropower project types are: run of river, reservoir based and pumped storage.

Typical impacts ranging from negative to positive are well known both from environmental and social aspects. Good experience gained during past decades in combination with new sustainability guidelines, innovative planning based on stakeholder consultations and scientific know-how is promising with respect to securing a high sustainability performance in future hydropower projects. Transboundary water management, including hydropower projects, establishes an arena for international cooperation what may contribute to promote peace, security and sustainable economic growth. Ongoing research on technical (e.g. variable speed generation), silt erosion resistive material and environmental issues (e.g. fish friendly turbines) may ensure continuous improvement and enhanced outcomes for future projects.

Renovation, modernisation & upgrading (RM&U) of old power stations is cost effective, environment friendly and requires less time for implementation. There is a substantial potential for adding hydropower generation components to existing infrastructure like weirs, barrages, canals and ship locks. About 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes. Only 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multi-purpose reservoirs.

Hydropower is providing valuable energy services as the generating units can be started or stopped almost instantly. It is the most responsive energy source for meeting peak demands and balancing unstable electricity grids, which enhances energy security. Storage hydropower therefore is ideal for

backing up and regulating the intermittent renewable sources like wind, solar and waves, thus allowing for a higher deployment of these sources in a given grid. Also the flexibility and short response time may facilitate nuclear and thermal plants to operate at their optimum steady state level thereby reducing their fuel consumption and emissions. Life cycle analysis indicates that hydropower is among the cleanest electricity options with a low carbon footprint. For the time being, 1163 hydropower projects are in the CDM pipeline, represent 26% of CDM applications. However, very few projects have so far received credits.

In addition to mitigate global warming, hydropower with storage capacity can also mitigate freshwater scarcity by providing water security during lean flows and drought in dry regions of the world. By 2035, it is projected that 3 billion people will be living in conditions of severe water stress. Water, energy and climate change are inextricably linked. Water storage facilities have an important role in providing energy and water for sustainable development. It is anticipated that climate change will lead to modifications of the hydrological regimes in many countries, introducing additional uncertainty into water resources management. In order to secure water and energy supply in a context of increasing hydrological variability, it will be necessary to increase investment in infrastructure sustaining water storage and control.

Creating reservoirs is often the only way to adjust the uneven distribution of freshwater in space and time. Freshwater is an essential resource for human civilisation. For this reason freshwater storage is a mean to respond to manifold needs, such as water supply, irrigation, flood control and navigation. Sitting at the nexus of water and energy, multipurpose hydropower projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs, helping to secure freshwater availability.

5.1 Introduction

5.1.1 History

Hydropower, hydraulic power or water power is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the widespread availability of commercial electric power, hydropower was used for irrigation and operation of various machines, such as watermills, textile machines and sawmills etc. By using water for power generation, people have worked with nature to achieve a better lifestyle. The mechanical power of falling water is an age-old tool. It was used by the Greeks to turn water wheels for grinding wheat into flour, more than 2,000 years ago. In the 1700's mechanical hydropower was used extensively for milling and pumping. During the 1700s and 1800s, water turbine development continued. In 1880, a brush arc light dynamo driven by a water turbine was used to provide theatre and storefront lighting in Grand Rapids, Michigan; and in 1881, a brush dynamo connected to a turbine in a flour mill provided street lighting at Niagara Falls, New York. The breakthrough came when the electric generator was coupled to the turbine, which resulted in the world's first hydroelectric station was commissioned on September 30, 1882 on Fox River at Vulcan Street Plant Appleton, Wisconsin, USA (United States Bureau of Reclamation USBR).

Contemporary hydropower plants generate anywhere from a few kW, enough for a single residence, to several thousands of MW, power enough to supply a large city and region. Early hydropower plants were much more reliable and efficient than the fossil fuel fired plants of the day. This resulted in a proliferation of small to medium sized hydropower stations distributed wherever there was an adequate supply of moving water and a need for electricity. As electricity demand grew, coal and oil fuelled power plants increased. Several of hydropower plants involved large dams which submerged land to provide water storage. This has caused great concern for environmental impacts. Historically regional hydropower generation during 1965 to 2007 has been shown in figure 5.1.

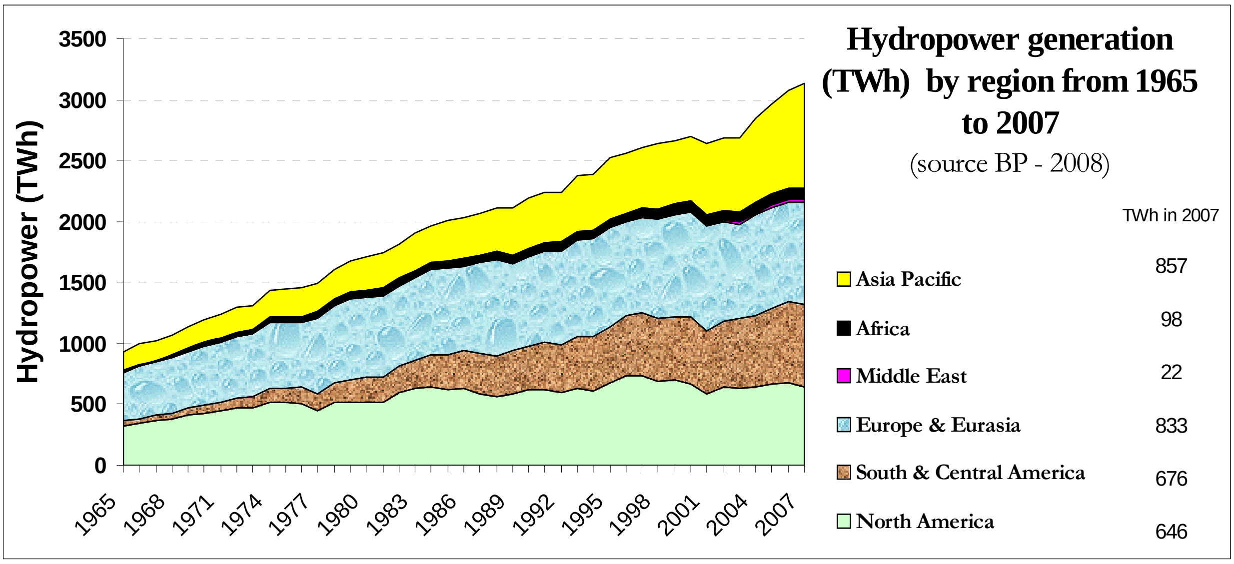

Figure 5.1: Hydropower generation (TWh) by region (BP, 2008).

5.1.2 Classification (size, head, storage capacity and purpose)

Hydropower was the first technology to generate electricity from a renewable source and is presently the only large-scale renewable where the largest plants produce between 80-100 TWh/year (Itaipu-Brazil and Three Gorges-China). Hydropower installations could be seen as a continuum. They are always site-specific and thus designed according to the river system they inhabit. Its great variety in size gives the additional ability to meet large centralized urban energy needs as well as decentralized rural needs. In addition to mitigating climate change, hydropower’s flexibility in size also creates opportunities towards meeting an increasing need for freshwater. Impacts on ecosystems will vary not according to installed effect or whether or not there is a reservoir but will be decided by the design, where various intakes, dams and waterways are situated and how much water flow is used for power generation. The idea of small (SHP) and large hydro gives an impression of small or large negative impacts. This generalization will not hold as it is possible to construct rather large power plants with moderate impacts while the cumulative effects of several small power plants may be more adverse than one larger plant in the same area. Based on this it is more fruitful to evaluate hydropower based on its sustainability performance and based on the type of electricity service (intermittent, base or peak load) supplied as opposed to a classification based on technical units with little or no relevance for nature or society.

According to the IEA (2000b), hydropower projects can be classified by a number of ways which are not mutually exclusive:

5.1.2.1 By size (large, medium, small, mini, micro, pico)

The classification according to installed capacity is the most frequent form of classification used. Yet, there is no worldwide consensus on definitions regarding size categories, mainly because of different development policies in different countries. Based on installed capacity of hydropower projects, classification of hydropower varies from country to country. A general classification may be taken as:

- pico < 0,005 MW
- micro < 0,1 MW
- mini < 1 MW
- small > 1-100 MW
- medium > 100 MW
- large > 500 MW

Chamuera, Rätia, Switzerland (0,55 MW)

Macagua, Venezuela (15,910 MW)

Small hydropower plants have the same components as large ones. Small hydropower has been developed by many countries, especially the developing countries. Compared to large hydropower, it takes less time and efforts to integrate small hydro schemes into local environments. It has been increasingly used in many parts of the world as an alternative energy source, especially in remote areas where other power sources are not viable. These power systems can be installed in small rivers or streams with little or marginal environmental effect. Most small hydro power systems do not require the construction of a dam, but are rather run of river schemes.

Small hydro in isolated systems may be also connected to grid, if available at a later date. Such integration with a grid shall improve the total benefits of hydropower projects and quantum shall be as per site-specific conditions. Comparative advantage of the small hydro has already resulted in a large number of these installations all over the world. The success of the small hydro option depends on careful selection and timely completion of the best sites.

The redundancies in terms of stake are reduced. All small hydropower are designed to be failing safe. The local availability of construction materials often helps in implementing the small hydropower project.

5.1.2.2 By head (high or low)

How high the water pressure on the turbines is will be basically determined by the gravity force of the falling water used. The difference between the upper water level and the lower is called head (vertical height of water above the turbine). Consequently, the type of head together with the discharge is a basic parameter for deciding the type of hydraulic turbine to be used. Higher heads involve major civil works whereas low heads involve higher electro-mechanical works. Generally, for high heads Pelton turbines are used, whereas Francis turbines are used to exploit medium heads. For low heads commonly Kaplan and bulb turbines are applied.

Head may be classified as follows:

• High Head	75 m above
• Medium Head	40-75 m
• Low head	3-40 m
• Ultra Low Head	< 3 m

High head project Tyssedal Power Plant, Norway (UNESCO Heritage site),

Low head power plant (45MW) Rivières-des-Prairies, (head 7,5 m) Montreal, Canada

5.1.2.3 By purpose (single or multi-purpose)

As hydropower does not consume the water that drives the turbines, this renewable resource is available for various other uses essential for human subsistence. In fact, a significant proportion of hydropower projects are designed for multiple purposes. Accordingly to Jacques Lecornu (1998) about the third of all hydropower projects takes on various other functions aside from generating electricity. They prevent or mitigate floods and droughts, they provide the possibility to irrigate agriculture, to supply water for domestic, municipal and industrial use as well as they can improve conditions for navigation, fishing, tourism or leisure activities.

One aspect often overlooked when addressing hydropower and the multiple uses of water is that the power plant, as a revenue generator, in some cases pays for the facilities required to develop other water uses, which might not generate sufficient direct revenues to finance their construction.

Hoover Dam and Lake Mead (USA)

hosts some 12 million visitors each year. The waters of Lake Mead are used to supply 18 million people in cities, towns and Indian communities in the states of Arizona, Nevada and California. In addition, agricultural land totalling 4,000 km2 in USA and 2000 km2 in Mexico is supplied with irrigation water, and the power plant supplies 4 billion kWh/year.

Based on hydrological relation, hydropower plants can moreover be classified into stand-alone hydropower plants and cascade hydropower plants.

5.1.3 Maturity of technology

Hydropower is a proven and well advanced technology based on more than a century of experience. Hydropower schemes are robust, high-efficient and good for long-term investments with life spans of 40 years or more. Hydropower plants are unique, the planning and construction is expensive and the lead times are long. The annual operating and maintenance costs are very low compared with the capital outlay. Hydro provides an extraordinary level of services to the electric grid. The production of peak load energy from hydropower allows for the optimisation of base-load power generation from other less flexible sources such as nuclear and thermal power plants.

Hydropower has the best conversion efficiency of all known energy sources (~90%, water to wire) due to its direct transformation of hydraulic energy to electricity. It has the most favourable energy payback ratio considering the amount of energy required to build, maintain and fuel of a power plant compared with the energy it produces during its normal life span (see 5.4).

5.2 Resource potential

5.2.1 Worldwide Hydropower Potential

The International Journal of Hydropower & Dams 2005 and World Atlas & Industry Guide (IJHD, 2005) probably provides the most comprehensive inventory of current installed capacity, annual generation, and hydropower potential. The Atlas provides three measures of hydropower potential: gross theoretical, technically feasible, and economically feasible all as potential annual generation (TWh/year). The technically feasible potential values for the six regions of the world have been chosen for this discussion considering that gross theoretical potential is of no practical value and what is economically feasible is variable depending on energy supply and pricing.

The total worldwide generation potential is 14,368 TWh (IJHD, 2005) with a corresponding estimated total capacity potential of 3,838 MW[1]; five times the current installed capacity. The generation and capacity potentials for the six world regions are shown in Figure 5.2. Pie charts included in the figure provide a comparison of the capacity potential to installed capacity for each region and the percentage that the potential capacity (undeveloped capacity) is of the combination of potential and installed capacities. These charts illustrate that undeveloped capacity ranges from about 70 percent in Europe and North America to 95 percent in Africa indicating large opportunities for hydropower development worldwide.

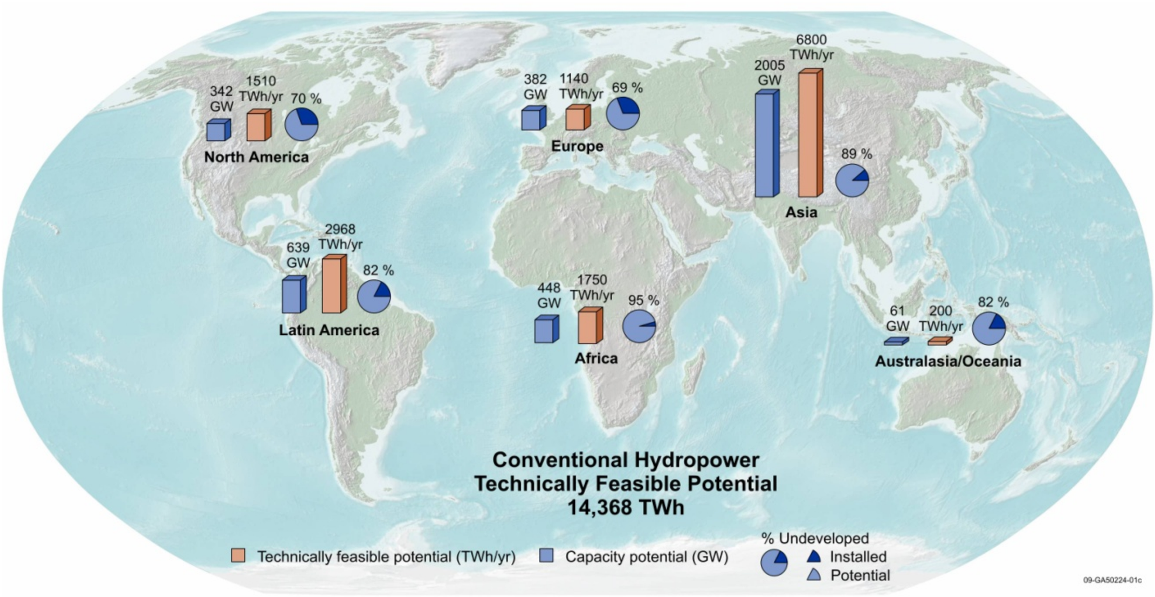

Figure 5.2: Regional hydropower potential in annual generation and capacity with comparison of installed and potential capacities including potential capacity as percent undeveloped (Source: (IJHD, 2005).

There are several notable features of the data in Figure 5.2. North America and Europe, that have been developing their hydropower resources for more than a century still have the sufficient potential to double their hydropower capacity; belying the perception that the hydropower resources in these highly developed parts of the world are “tapped out”. Most notably Asia and also Latin America have outstandingly large potentials and along with Australasia/Oceania have very large potential hydropower growth factors (450 to almost 800%). Africa has higher potential than either North America or Europe, which is understandable considering the comparative states of development. However, compared to its own state of hydropower development, Africa has the potential to develop 21 times the amount of hydropower currently installed.

An understanding and appreciation of hydropower potential is best obtained by considering current total regional installed capacity and annual generation (2003/2004) (IJHD, 2005) shown in Figure 5.3. The 2005 reported worldwide total installed hydropower capacity is 746 GW producing a total annual generation of 2,794 TWh (IJHD, 2005) Figure 5.3 also includes regional average capacity factors calculated using regional total installed capacity and annual generation [capacity factor = generation/(capacity x 8760hrs)].

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[1] Derived value based on regional generation potentials (IJHD, 2005) and average capacity factors shown in Figure 5.3.

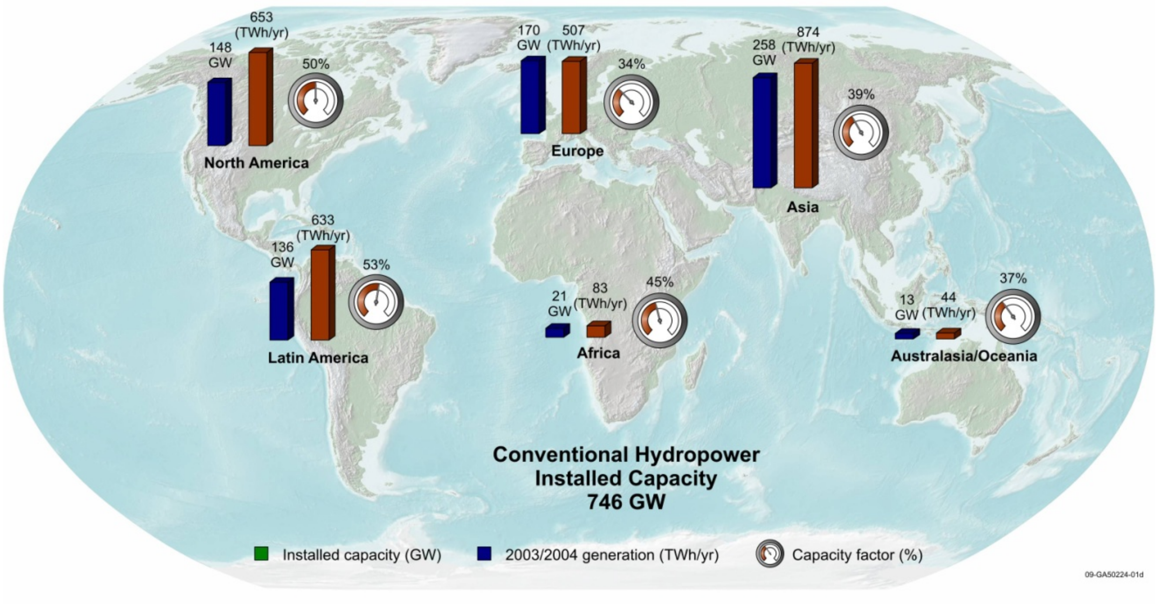


Figure 5.3: Total regional installed capacity, 2003/2004 annual generation, and average capacity factor (Source: (IJHD, 2005). [TSU: colour-coding in figure not consistent]

It is interesting to note that North America, Latin America, Europe, and Asia have the same order of magnitude of total installed capacity and not surprisingly, Africa and Australasia/Oceania have an order of magnitude less – Africa due to underdevelopment and Australasia/Oceania because of size, climate, and topography. It is also noteworthy that the capacity factors are in the range to be expected although the value for Europe (34%) is surprising low perhaps due to the use of one year of data. If this value along with those for Asia (39%) and Australasia/Oceania (37%) are actually representative, it could indicate an opportunity for increased generation through equipment upgrades and operation optimization. Potential generation increases achievable by equipment upgrades and operation optimization have generally not been assessed.

The regional potentials presented above are for conventional hydropower corresponding to sites on natural waterways where there is significant topographic elevation change to create useable hydraulic head. Hydrokinetic technologies that do not require hydraulic head but rather extract energy in-stream from the current of a waterway are being developed. These technologies increase the potential for energy production at sites where conventional hydropower technology cannot operate. Non-traditional sources of hydropower are also not counted in the regional potentials presented above. Examples are constructed waterways such as water supply systems, aqueducts, canals, effluent streams, and spillways. Applicable conventional and hydrokinetic technologies can produce energy using these resources. The generation potential of in-stream and constructed waterway resources has not been assessed, but they are undoubtedly significant sources of emissions-free energy production based on their large extent.

Worldwide, hydropower has sufficient undeveloped potential to increase its role significantly as a large scale energy source. It can produce electricity with negligible green house gas emissions compared to the fossil energy sources currently in wide spread use. For this reason, hydropower has an important future role to play in mitigating climate change.

5.2.2 Impact of climate change on resource potential

The resource potential for hydropower is currently based on historical data for the present climatic conditions. With a changing climate, this potential could change due to:

1) Changes in river flow (runoff) related to changes in local climate, particularly on precipitation and temperature in the catchment area. This may lead to changes in runoff volume, variability of flow and in the seasonality of the flow, for example by changing from spring/summer high flow to more winter flow, directly affected the potential for hydropower generation;

2) Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects:

3) Changes in sediment loads due to changing hydrology and extreme events. More sediment could increase turbine abrasions and decrease efficiency. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation, increasing flood spill and decreasing generation.

The most recent IPCC study of climate change, Assessment Report 4 (AR4), was published in 2007 (IPCC, 2007a). Possible impacts were studied by Working group II (WGII) and reported in (IPCC, 2007c). Here, impacts on water resources were also studied and discussed. Later, a Technical paper on Water was prepared based on the work in WGII and other sources (Bates *et al.*, 2008). The information presented here is mostly based on these sources, but also a few additional papers and reports published in 2008 and 2009 in order to assure that it is as up to date as possible.

5.2.2.1 Projected changes in precipitation

Climate change projections for the 21st century were developed in AR4. The projections were based on four different scenario families or "Storylines": A1, A2, B1 and B2, each considering a plausible scenario for changes in population and economic activity over the 21st century (IPCC, 2007b). The different storylines were used to form a number of emission scenarios, and each of these were used as input to a range of climate models. Therefore, a wide range of possible future climatic projections have been presented, with corresponding variability in projection of precipitation and runoff (IPCC 2007c) (Bates *et al.*, 2008)

Climate projections using multi-model ensembles show increases in globally averaged mean water vapour, evaporation and precipitation over the 21st century. A summary of results are shown in figure 5.4. At high latitudes and in part of the tropics, all or nearly all models project an increase in precipitation, while in some sub-tropical and lower mid-latitude regions precipitation decreases in all or nearly all models. Between these areas of robust increase or decrease, even the sign of precipitation change is inconsistent across the current generation of models (Bates *et al.*, 2008).

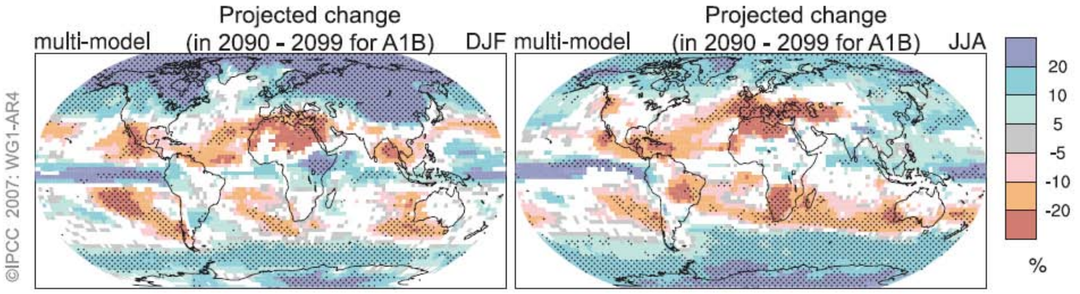


Figure 5.4: Projected multi-model mean changes in global precipitation for the SRES A1B Emission scenario. December to February at left, June to August at right. Changes are plotted only where more than 66% of the models agree on the sign of the change. The stippling indicates areas where more than 90% of the models agree on the sign of the change. [AR4 WG1 TS]

5.2.2.2 Projected changes in river flow

Changes in river flow due to climate change will primarily depend on changes in volume and timing of precipitation and evaporation. A large number of studies of the effect on river flow have been published and were summarized in AR4. Most of these studies use a catchment hydrological model driven by climate scenarios based on climate model simulations. A few global-scale studies have used runoff simulated directly by climate models [WGI 10.2.3.2] and hydrological models run off-line. [WGII 3.4] The results from these studies show increasing runoff in high latitudes and the wet tropics and decreasing runoff in mid-latitudes and some parts of the dry tropics. A summary of the results are shown in Figure 5.5.

Uncertainties in projected changes in the hydrological systems arise from internal variability in the climatic system, uncertainty in future greenhouse gas and aerosol emissions, the translations of these emissions into climate change by global climate models, and hydrological model uncertainty. Projections become less consistent between models as the spatial scale decreases. The uncertainty of climate model projections for freshwater assessments is often taken into account by using multi-model ensembles (Bates *et al.*, 2008).

The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here (Bates *et al.*, 2008).

5.2.2.3 Projected effects on hydropower potential – Studies in AR4

Hydropower potential depends on topography and volume, variability and seasonal distribution of runoff. An increase in climate variability, even with no change in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built. Generally, the regions with increasing precipitation and runoff will have increasing potential for hydropower production, while regions with decreasing precipitation and runoff will face a reduction in hydropower potential.

In order to make accurate quantitative predictions it is necessary to analyze both changes in average flow and changes in temporal distribution of flow, using hydrological models to convert time-series of climate scenarios into time-series of runoff scenarios. In catchments with ice, snow and glaciers it is of particular importance to study the effects of changes in seasonality, because a warming climate will often lead to increasing winter runoff and decreasing runoff in spring and summer. A shift in winter precipitation from snow to rain due to increased air temperature may lead to a temporal shift in stream peak flow and winter conditions (Stickler *et al.*, 2009) in many continental and mountain regions. The spring snowmelt peak is brought forward or eliminated entirely, and winter flow increases. As glaciers retreat due to warming, river flow increase in the short term but decline once the glaciers disappear (Kundzewicz *et al.*, 2008).

A number of studies of the effects on hydropower from climate change have been published, some reporting increased and some decreased hydropower potential. A summary of some of the findings related to hydropower can be found in (Bates *et al.*, 2008) largely based on work in WGII. A summary from these findings are given below for each continent, with reference to WGII and relevant chapters:

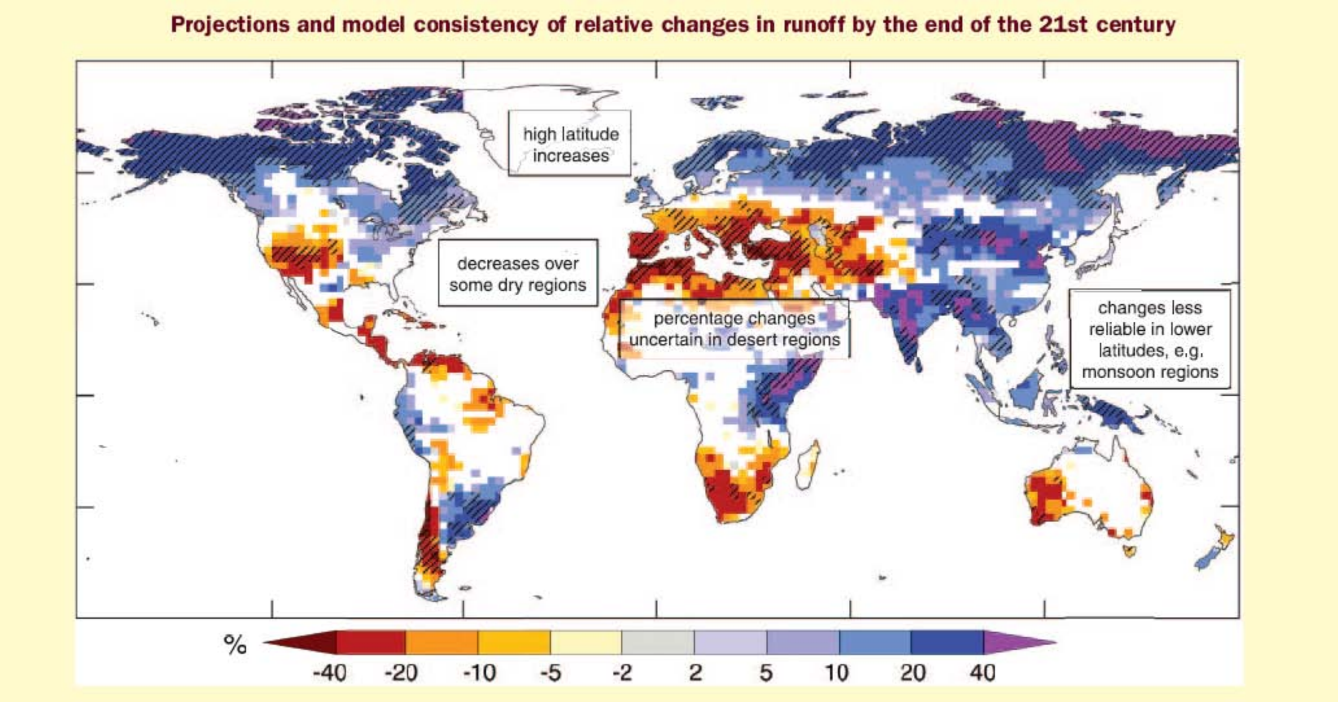


Figure 5.5: Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change (Bates et al., 2008).

5.2.2.3.1 Africa

The electricity supply in the majority of African States is derived from hydro-electric power. There are few available studies that examine the impacts of climate change on energy use in Africa [WGII 9.4.2]

5.2.2.3.2 Asia

Changes in runoff could have a significant effect on the power output of hydropower-generating countries such as China, India, Iran and Tajikistan etc.

5.2.2.3.3 Europe

Hydropower is a key renewable energy source in Europe (19.8% of the electricity generated). By the 2070s, hydropower potential for the whole of Europe is expected to decline by 6%, translated into a 20–50% decrease around the Mediterranean, a 15–30% increase in northern and Eastern Europe, and a stable hydropower pattern for western and central Europe. [WGII 12.4.8.1]

5.2.2.3.4 Australia and New-Zealand

In Australia and New Zealand, climate change could affect energy production in regions where climate-induced reductions in water supplies lead to reductions in feed water for hydropower turbines and cooling water for thermal power plants. In New Zealand, increased westerly wind speed is very likely to enhance wind generation and spillover precipitation into major South Island hydro-catchments, and to increase winter rain in the Waikato catchment (Ministry for the Environment, 2004). Warming is virtually certain to increase melting of snow, the ratio of rainfall to snowfall, and river flows in winter and early spring. This is very likely to assist hydro-electric generation at the time of peak energy demand for heating. [WGII 11.4.10]

5.2.2.3.5 South-America

Hydropower is the main electrical energy source for most countries in Latin America, and is vulnerable to large-scale and persistent rainfall anomalies due to El Niño and La Niña, as observed in Argentina, Colombia, Brazil, Chile, Peru, Uruguay and Venezuela. A combination of increased energy demand and droughts caused a virtual breakdown of hydro-electricity in most of Brazil in 2001 and contributed to a reduction in GDP. Glacier retreat is also affecting hydropower generation, as observed in the cities of La Paz and Lima. [WGII 13.2.2, 13.2.4]

5.2.2.3.6 North-America

Hydropower production is known to be sensitive to total runoff, to its timing, and to reservoir levels. During the 1990s, for example, Great Lakes levels fell as a result of a lengthy drought, and in 1999 hydropower production was down significantly both at Niagara and Sault St. Marie. [WGII 4.2] For a 2–3°C warming in the Columbia River Basin and British Columbia Hydro service areas, the hydro-electric supply under worst-case water conditions for winter peak demand will be likely to increase (high confidence). Similarly, Colorado River hydropower yields will be likely to decrease significantly, as will Great Lakes hydropower. Lower Great Lake water levels could lead to large economic losses (Canadian $437–660 million/yr), with increased water levels leading to small gains (Canadian $28–42 million/yr). Northern Québec hydropower production would be likely to benefit from greater precipitation and more open water conditions, but hydro plants in southern Québec would be likely to be affected by lower water levels. Consequences of changes in seasonal distribution of flows and in the timing of ice formation are uncertain. [WGII 3.5, 14.4.8]

5.2.2.3.7 An assessment of global effect on hydropower resources

The studies reviewed in the literature predict both increasing and decreasing effect on the hydropower production, mainly following the expected changes in river runoff. So far no total figures have been presented for the global hydropower system.

In a recent study by Hamududu & Killingtveit (2010), the global effects on existing hydropower system were studied, based on previous global assessment of changes in river flow (Milly *et al.*, 2008) for the SRES A1B scenario using 12 different climate models. The estimated changes in river flow were converted to %-wise changes for each country in the world, compared to the present situation. For some of the largest and most important hydropower producing countries, a finer division into political regions were used (USA, Canada, Brazil, India, China and Australia). The changes in hydropower generation for the existing hydropower system (as per 2005) were then computed for each country/region, based on changes in flow predicted from the climate models. Some of the results are summarized in Table 5.1.

The somewhat surprising result from this study is that only very small total changes seem to occur for the present hydropower system, even if individual countries and regions could have significant changes in positive or negative direction, as shown in the site-specific or regional studies (section 5.2.2.3). The future expansion of the hydropower system will probably mainly occur in the same areas as the existing system, since this is where most of the potential sites are located. Therefore, it can probably be stated that the total effects of climate change on the total hydropower potential will be small, when averaged over continents or globally.

Table 5.1: Power generation capacity in GW and TWh/year (2005) and estimated changes (TWh/year) due to climate change by 2050. Results are based on analysis for SRES A1B scenario for 12 different climate models (Milly et al., 2008) and data for the hydropower system in 2005 (DOE, 2009). Results from Hamududu & Killingtveit (2010).

Region	Power prod. capacity (2005)		Change by 2050 (TWh/yr)
	GW	TWh/yr	
Africa	22	90	0.0
Asia	246	996	2.7
Europe	177	517	-0.8
North America	161	655	0.3
South America	119	661	0.3
Oceania	13	40	0.0
TOTAL	**737**	**2931**	**2.5**

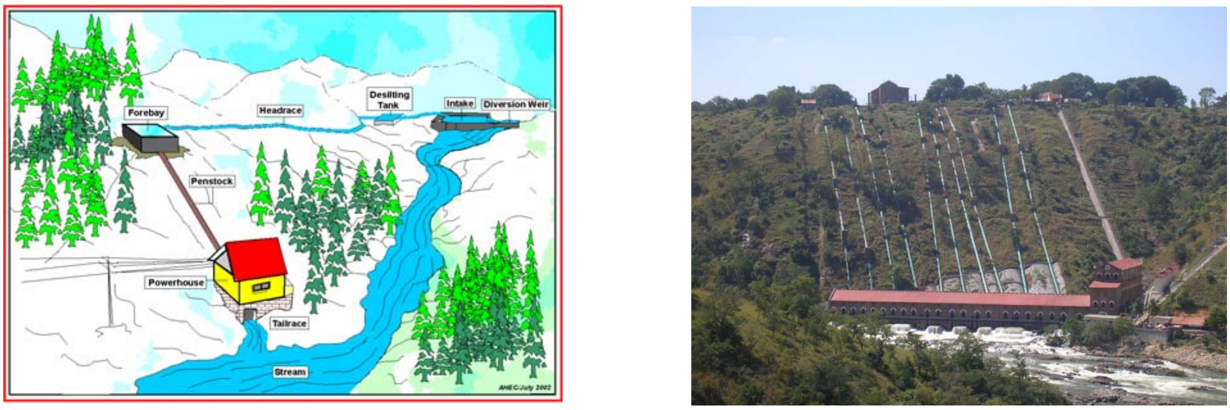
5.3 Technology and applications

5.3.1 Types

HPP are often classified in three main categories according to operation and type of flow. Run of river (ROR), reservoir based and pumped storage type projects are commonly used for different applications and situations. Hydropower projects with a reservoir also called storage hydropower deliver a broad range of energy services such as base load, peak, energy storage and acts as a regulator for other sources. Storage hydro also often delivers additional services which are going far beyond the energy sector such as flood control, water supply, navigation, tourism and irrigation. Pumped storage delivers its effect mainly when consumption is peaking. RoR HPP only has small intake basins with no storage capacity. Some RoR HPP also has small storage and are known as pondage-type plants. Power production therefore follows the hydrological cycle in the watershed. For RoR HPP the generation varies as per water availability from rather short in the small tributaries to base-load in large rivers with continuous water flow.

5.3.1.1 Run of River (RoR)

A Run of river hydropower plant draws the energy for electricity production mainly from the available flow of the river. Such a hydropower plant generally includes some short-term storage (hourly, daily, or weekly), allowing for some adaptations to the demand profile. Run-of-river hydropower plants are normally operated as base-load power plants. A portion of river water might be diverted to a channel, pipe line (penstock) to convey the water to hydraulic turbine which is connected to an electricity generator. Figure 5.6 shows such type of scheme. Their generation depends on the precipitation of the watershed area and may have substantial daily, monthly, or seasonal variations. Lack of storage may give the small RoR hydropower plant situated in small rivers or streams the characteristics of an intermittent source. Installation of small RoR plants is relatively cheap and has in general only minor environmental impacts. However, the relatively low investment does not allow putting aside a significant amount of financial resources for mitigation. In contrast large projects may spend substantial resources on mitigating environmental and social impacts. An example is the Theun Hinboun Expansion Project (280 MW installed effect) now under construction in Laos that has a budget of app. 50 mill USD for mitigating such impacts and for enhancing opportunities (Theun-Hinboun-Project, 2008)



(Shivasamudram, heritage, India)

Figure 5.6: Run of river hydropower plant.

5.3.1.2 Reservoir

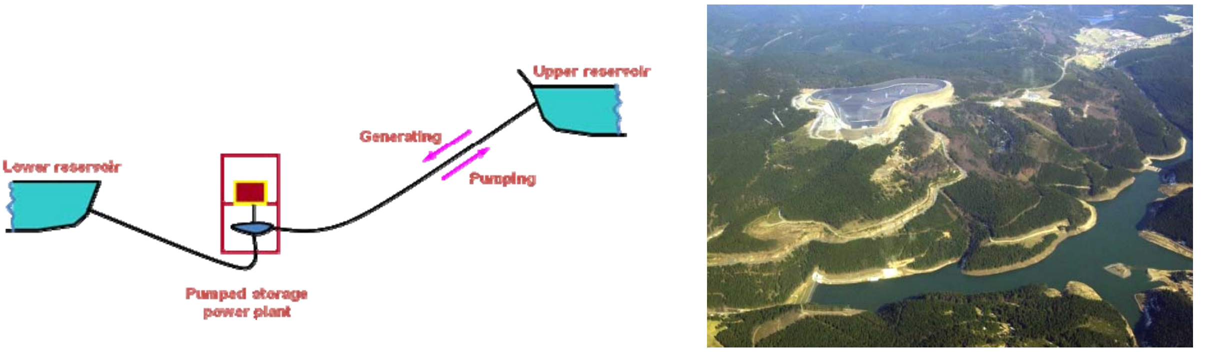
In order to reduce the dependence on the variability of inflow, many hydropower plants comprise reservoirs where the generating stations are located at the dam toe or further downstream through tunnel or pipelines as per the electricity or downstream water demand (Figure 5.7). Such reservoirs are often situated in river valleys. High altitude lakes make up another kind of natural reservoirs. In these types of settings the generating station is often connected to the lake serving as reservoir via tunnels coming up beneath the lake (lake tapping). For example, in Scandinavia natural high altitude lakes are the basis for high pressure systems where the heads may reach over 1000 m. The design of the HPP and type of reservoir that can be built is very much dependent on opportunities offered by the landscape.

(1,528 MW)Manic-5, Québec, Canada

Figure 5.7: Hydropower plants with reservoir.

5.3.1.3 Pumped-storage

Pumped-storage plants pump water into an upper storage basin during off-peak hours using surplus electricity from base load power plants and reverse flow to generate electricity during the daily peak load period. It is considered to be one of the most efficient technologies available for energy storage. Figure 5.8 shows such type of development.



(Goldisthal, Thüringen Germany)

Figure 5.8: Pumped storage project (Source: IEA, 2000b).

5.3.1.4 Instream technology using existing facilities

To optimise existing facilities like weirs, barrages, canals or falls, small turbines can be installed for electricity generation. These are basically functioning like a run-of-river scheme shown in Figure 5.9.

(Narngawal,, India)

Figure 5.9: Typical arrangement of instream technology hydropower projects.

5.3.2 Status and current trends in technology development

5.3.2.1 Efficiency

The potential for energy production in a hydropower plant will be determined by these main parameters given by the hydrology, topography and design of the power plant:

1) The amount of water available, Q_T (Million m^3 of water pr year = Mm^3/year)
2) Water loss due to flood spill, bypass requirements or leakage, Q_L (Mm^3/year)
3) The difference in head between upstream intake and downstream outlet, H_{gr} (m)
4) Hydraulic losses in water transport due to friction and velocity change, H_L (m)
5) The efficiency in energy conversion in electromechanical equipment, η

When these parameters are given, the total average annual energy, E_a (GWh/year) that can be produced in the power plant can be calculated by the formula (ρ is density of water in kg/m^3 , g is the acceleration of gravity of 9.81 ms^{-2} and C is a unit conversion factor):

$$E_a = (Q_T - Q_L) \cdot (H_{gr} - H_L) \cdot \eta \cdot \rho \cdot g \cdot C \qquad \text{(GWh/year)}$$

The total amount of water available at the intake (Q_T) will usually not be possible to utilize in the turbines because some of the water (Q_L) will be lost. This loss occurs because of spill of water during high flows when inflow exceeds the turbine capacity, because of bypass releases for environmental flows and because of leakage.

In the hydropower plant the potential (gravitational) energy in water is transformed into kinetic energy and then mechanical energy in the turbine and further to electrical energy in the generator. The energy transformation process in modern hydropower plants is highly efficient, usually with well over 90% mechanical efficiency in turbines and over 99% in the generator. Old turbines can have lower efficiency, and it can also be reduced due to wear and abrasion caused by sediments in the water. The rest of the potential energy (100- η) is lost as heat in the water and in the generator.

In addition, there will be some energy losses in the head-race section where water flows from the intake to the turbines, and in the tail-race section taking water from the turbine back to the river downstream. These losses, called head loss (H_L), will reduce the head and hence the energy potential for the power plant. These losses can be classified either as friction losses or singular losses. Friction losses in tunnels, pipelines and penstocks will depend mainly on water velocity and the roughness.

The total efficiency of a hydropower plant will be determined by the sum of these three loss components. Loss of water can be reduced by increasing the turbine capacity or by increasing the reservoir capacity to get better regulation of the flow. Head losses can be reduced by increasing the area of head-race and tail-race, by decreasing the roughness in these and by avoiding too many changes in flow velocity and direction. The efficiency in electromechanical equipment, especially in turbines, can be improved by better design and also by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow. Different turbines types have quite different efficiency profiles when the turbine discharge deviates from the optimal value, see Figure 5.10.

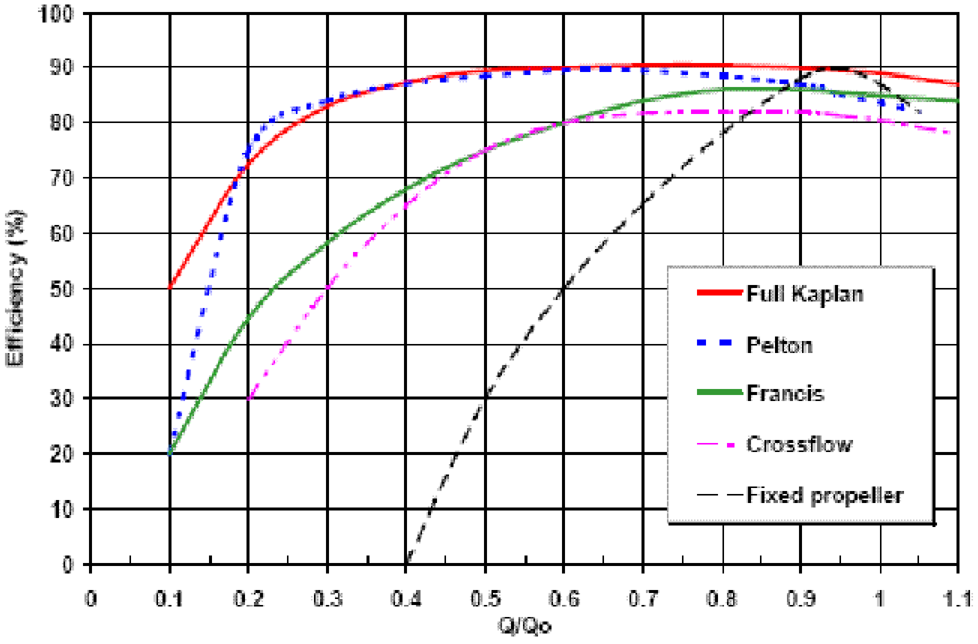


Figure 5.10: Typical efficiency curves for different types of hydropower turbines.

5.3.2.1 Tunneling capacity

5.3.2.1.1 Tunneling technology

In hydropower projects tunnels in hard rock are mainly used for transporting water from the intake to the turbines (head-race), and from the turbine back to the river, lake or fjord downstream (tail race). In addition, tunnels are used for a number of other purposes especially where the power station is placed underground.

Tunnelling technology has improved very much due to introduction of increasingly efficient equipment, as illustrated by Figure 5.11 (Zare *et al.*, 2007).

Today, the two most important technologies for hydropower tunnelling are:

- Drill and Blast method
- Tunnel boring machines

5.3.2.1.2 Drill and Blast method (D&B)

D&B is the conventional method for tunnel excavation in hard rock. In the D&B method, a drilling rig (“jumbo”) is used to drill a predetermined pattern of holes to a selected depth in the rock face of the proposed tunnel’s path. The drilled holes are then filled with explosives such as dynamite. The charges are then detonated, causing the rock to crack and break apart. The loosened debris or muck is then dislodged and hauled away. After the broken rock is removed the tunnel must be secured, first by scaling (removing all loose rock from roof and walls) and then by stabilizing the rock faces permanently. For more details, see below.

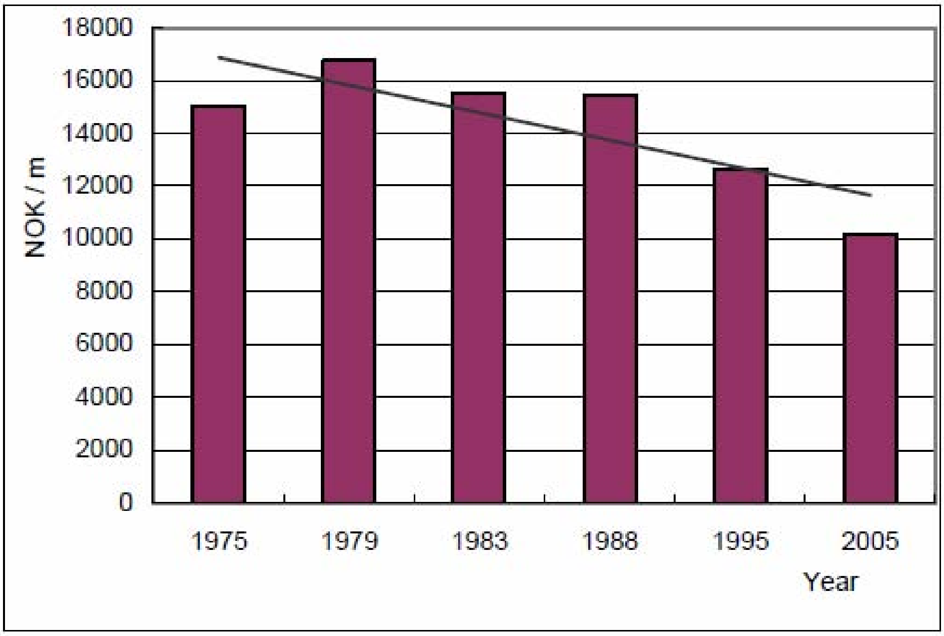


Figure 5.11: Development in tunneling technology - trend of excavation costs for a 60 m2 tunnel, price level 2005, Norwegian Kroner (NOK) pr m. (Zare et al., 2007).

5.3.2.1.3 Tunnel Boring Machines (TBM)

TBM excavates the entire cross section in one operation without the use of explosives. TBM’s carry out several successive operations: drilling, support of the ground traversed and construction of the tunnel. During drilling, the cutting wheel turns on its axis under high pressure and the cutting wheels break up the rock. At the same time, the chutes receive the excavated material and drop them at the base of the shield in the operating chamber, from where they are removed. As drilling progresses, the TBM installs the segments constituting the walls of the tunnel. These are carried by the transporter system then taken towards the erectors, who install them under cover of the shield's metal skirt. The TBM can then be supported and move forward, using its drive jacks.

The TBMs are finalized and assembled on each site. The diameter of tunnels constructed can be up to 15 meters. The maximum excavation speed is typically from 30 up to 60 meters per day.

5.3.2.1.4 Support and lining

To support the long term stability and safety of the tunnel, it may be necessary to support the rock from falling into the tunnel. The most used technique is rock bolting, other techniques with increasing cost are spraying concrete ("shotcrete"), steel mesh, steel arches and full concrete lining. The methods and principles for rock support in TBM tunnels are basically the same as in D&B tunnels, but because of the more gentle excavation and the stable, circular profile, a TBM tunnel normally needs considerably less rock support than a D&B tunnel. In Norway, the support cost for a TBM tunnel has been found to be 1/3 to 2/3 of the cost for a D&B tunnel of the same cross section.

In good quality rock the self-supporting capacity of the rock mass can be used to keep the amount of extra rock support to a minimum. In poor quality rock the design of support should be based on a good understanding of the character and extent of the stability problem. The most important geological factors which influence the stability of the tunnel and the need for extra rock support are: 1) The strength and quality of the intact rock 2) The degree of jointing and the character of the discontinuities 3) Weakness zones and faults 4) Rock stresses and 5) Water inflow (Edvardsen *et al.*, 2002).

The use of full concrete lining is an established practice in many countries, and these ads considerable to the cost and construction time for the tunnel. One meter of concrete lining normally costs from 3 to 5 times the excavation cost. Shotcrete is also quite expensive, from 1 to 1.2 times the excavation costs. Rock bolting is much cheaper, typically 0.6 times the excavation costs (Nilsen *et al.*, 1993).

In some countries, for example in Norway, the use of unlined tunnels and pressure shafts is very common. The first power plants with unlined pressure shafts were constructed in 1919 with heads up to 150 meters. Today, more than 80 high-pressure shafts and tunnels with water heads between 150 and up to almost 1000 meters are operating successfully in Norway (Edvardsen *et al.*, 2002).

5.3.3 Sedimentation Problem in Hydropower Projects

The problem of sedimentation is not caused by hydroelectric projects; nevertheless, it is one of the problems that need to be understood and managed. Fortunately there is a wealth of case studies (HARZA,1999) and literature in this regard to be able to deal with the problem (Graf, 1971). Sedimentation or settling of solids occurs in all basins and rivers in the world and it must be recognized and controlled by way of land-use policies and the protection of the vegetation coverage.

In every country, the land-used efforts are dedicated to determining and quantifying surface and subterranean hydrological resources, in order to assess the availability of water for human consumption and for agriculture. This is a great advantage for the development of hydroelectric projects, since this quantification is also entry level data for the potential amount of water that can be transformed into electrical energy. It is important to get measurements at different basins throughout the territory and all hydrometric stations, during wet and dry season, to be organized, analyzed and used for useful conclusions. Additionally, it is necessary to establish bathymetric control programs at all reservoirs for hydroelectric generation, which can be easily done by taking measurements every two years. To the previous results must be correlated with studies of basin or sub-basin erosion. Several models are available for these studies, one of which is the GIS (Geographical Information System).

The Revised Universal Soil Loss Equation (*RUSLE*) is a method that is widely utilized to estimate soil erosion from a particular parcel of land. In general the GIS model includes its calibration and using satellite images to determine the vegetation coverage for the entire basin, which determines the erosion potential of the sub-basins as well as the critical areas. The amount of sediment carried into a reservoir is at its highest during floods. Increases in average annual precipitation of only 10 percent can double the volume of sediment load of rivers (Patric, 2001). Reservoirs can then be affected significantly by the changes in sediment transport processes.

Reservoir sedimentation problems, due to a high degree of soil erosion and land degradation, are contributing to global water and energy scarcity. In many areas of the world average loss of surface water storage capacity due to sedimentation is higher than the volume increased due to new dam construction (White, 2005). In a World Bank study (Mahmood, 1987) it was estimated that about 0.5% to 1% of the total freshwater storage capacity of existing reservoirs is lost each year due to sedimentation. Similar conditions were also reported by (WCD, 2000; ICOLD, 2004).

The effect of sedimentation is not only reservoir storage capacity depletion over time due to sediment deposition, but also an increase in downstream degradation and increased flood risk upstream of the reservoirs. Sediment deposition in the reservoir can obstruct intakes to block the system from withdrawal of water. Hydropower projects can also suffer from wear of the turbines. The sediment-induced wear of the hydraulic machineries is more serious when the hydropower projects do not have room for storage of sediments. Lysne et al. (2003) reported the effect of sediment induced wear of turbines in power plants can be among others:

- Generation loss due to reduction in turbine efficiency
- Increase in frequency of repair and maintenance
- Increase in generation losses due to downtime
- Reduction in life time of the turbine and
- Reduction in regularity of power generation

All these effects are associated with revenue losses and increased maintenance cost during the operation of power plant.

Several promising concepts for sediment control at intake and removal of sediment from reservoirs and settling basin have been developed and practiced. A number of authors (Mahmood, 1987; Morris *et al.*, 1997; ICOLD, 1999; Palmieri *et al.*, 2003; White, 2005) have reported measures to mitigate the sedimentation problems. These measures can be generalised as measures to reduce sediment load to the reservoirs, remove sediment from the storage reservoirs, design and operate hydraulic machineries of hydropower plant aiming to resist effect of sediment passes through them.

However, it is not easy to apply them in all power plants. The application of most of the technical measures is limited to small reservoirs with a capacity inflow ratio of less than 3% and to reservoirs equipped with bottom outlet facilities. Each reservoir site has its own peculiarities and constraints. All alternatives will therefore not be suitable for all types of hydro projects. For efficient application of the alternative strategies, choices have to be made based on the assessment related to sediment characteristics, the shape and size of the reservoirs and its outlet facilities and operational conditions (Basson, 1997). Handling sediment in hydropower projects has therefore been a problem and remains a major challenge. In this context much research and development work remains and need to be done to address sedimentation problems in hydropower projects.

It is important to note that erosion control efforts are not exclusive to hydroelectric projects, but are an important part of national strategies for the preservation of water and land resources. Reforestation alone does not halt erosion; it must be complemented with land coverage and control of its human and animal usage.

5.3.4 Renovation and Modernization trends

Renovation, Modernisation & Uprating (RM&U) of old power stations is cost effective, environment friendly and requires less time for implementation. Capacity additions through RM&U of old power stations is an attractive proposition in the present scenario, when most of the power utilities on account of their financial conditions are not in a position to invest in setting up green field hydro power projects. The economy in cost and time essentially results from the fact that apart from the availability of the existing infrastructure, only selective replacement of critical components such as turbine runner, generator winding with class F insulation, excitation system, governor etc., and intake gates trash cleaning mechanism can lead to increase in efficiency, peak power and energy availability apart from giving a new lease on life to the power plant/equipment. RM&U may allow for restoring or improving environmental conditions in already regulated areas. An example is given in 5.6 (box). The Norwegian Research Council has recently initiated a program looking at so called win-win opportunities where the aim is to increase power production and at the same time improving environmental conditions (T. Forseth 2009).

Normally the life of hydro electric power plant is 30 to 35 years after which it requires renovation. The reliability of a power plant can certainly be improved by using modern equipments like static excitation, microprocessor based controls, electronic governors, high speed static relays, data logger, vibration monitoring, etc. Upgrading/uprating of hydro plants calls for a systematic approach as there are a number of factors viz. hydraulic, mechanical, electrical and economic, which play a vital role in deciding the course of action. For techno-economic consideration, it is desirable to consider the uprating along with Renovation & Modernization/Life extension. Hydro generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 807,000 MW of hydro equipment in operation today will need to be modernised by 2030 (SER2007). Having existing hydropower plants refurbished also result in incremental hydropower, both where present capacity has renovated or where existing infrastructure (like existing barrages, weirs, dams, canal fall structures, water supply schemes) has been reworked, adding new hydropower facilities.

There are 45,000 large dams in the world and the majority do not have a hydro component. A considerable number of these can have hydropower components without disturbing the existing downstream use. In India during 1997-2008 about 500 MW has been developed out of 4000 MW potential on existing structures.

5.3.5 Storage of water and energy

Water is stored in reservoirs which enable its uneven availability spatially as well as timely in a regulated manner to meet growing needs for water and energy in a more equitable manner. Hydropower reservoirs store rainwater and snow melt which after generating, can then be used for drinking or irrigation as water in neither is consumed or polluted in hydropower generation. By storing water, aquifers are recharged and reduce our vulnerability to floods and droughts. Studies have shown that the hydropower based reservoirs increase agriculture production and green vegetation covers downstream (Saraf *et al.*, 2001).

Reservoir based hydropower including pumped storage schemes may improve the performance of conventional thermal and nuclear power plants by harmonising the rapid changes in demand and facilitating thermal and nuclear plants to operate at their optimum steady state level. Such steady state operation reduces both fuel consumption and associated emissions.

5.4 Global and regional status of market and industry development

5.4.1 Existing generation, TWh/year (per region/total)

In 2006, the production of electricity from hydroelectric plants was 3,121 TWh compared to 1,295 TWh in 1973 (IEA, 2008), which represented an increase of 141% in this period. The major share of this percentage amount is the result of production in China and Latin America, which grew by 399.5 TWh and 562.2 TWh, respectively (Figure 5.12).

China, Canada, Brazil and the US together account for over 46% of the production (TWh) of electricity in the world and are also the four largest in terms of installed capacity (GW) of hydroelectric plants (IEA, 2008). Fig 5.13 shows the country wise hydropower generation. It is noteworthy that five out of the ten major producers of hydroelectricity are among the world's most industrialized countries: Canada, the United States, Norway, Japan and Sweden. This is no coincidence, given that the possibility of drawing on hydroelectric potential was decisive for the introduction and consolidation of the main electro-intensive sectors on which the industrialization process in these countries was based during a considerable part of the twentieth century. There are four major developing countries on the list of major hydroelectricity producers: Brazil, China, Russia and India. In these countries capitalism, although it developed later, seems to have followed in the footsteps of its predecessors [in the developed world], drawing on previously untapped energy to provide clean and safe energy, in sufficient quantities to guarantee the expansion of a solid industrial base (Freitas, 2003).

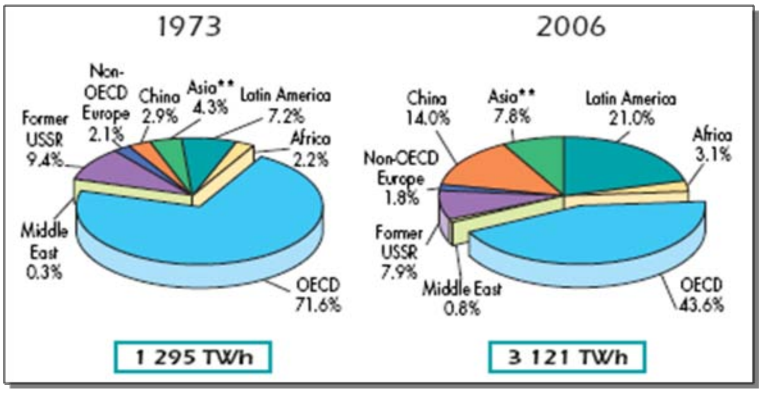


Figure 5.12: 1973 and 2006 regional shares of hydro production* (Source: IEA, 2008)

Hydro provides some level of power generation in 159 countries. Five countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The importance of hydroelectricity in the electricity matrix of these countries is, however, different (Table 5.2). On the one hand Brazil and Canada, are heavily dependent on this source having a percentage share of the total of 83.2% and 58% respectively. On the other hand United States has a share of 7.4% only from hydropower. In Russia, the share is 17.6% and 15.2% in China.

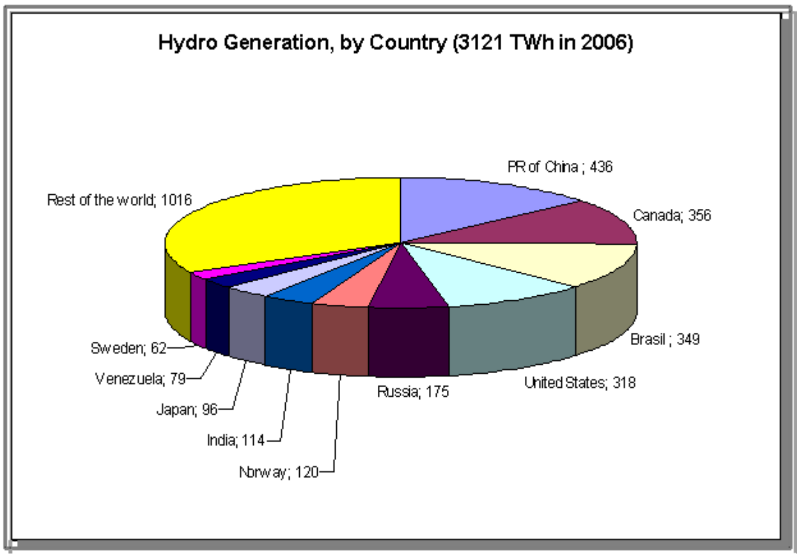


Figure 5.13: Hydro Generation by Country (TWh) (Source: IEA, 2008).

Table 5. 2: Major Countries Producers / Installed Capacity.

Installed Capacity Based on Production	**GW**
China	118
United States	99
Brazil	71
Canada	72
Japan	47
Russia	46
India	32
Norway	28
France	25
Italy	21
Rest of the world	308
World	**867**

2005 data

Sources: United Nations, IEA

Country Based on First 10 Producers	**% of Hydro in Total Domestic Electricity Generation**
Norway	98.5
Brazil	83.2
Venezuela	72.0
Canada	58.0
Sweden	43.1
Russia	17.6
India	15.3
China	15.2
Japan	8.7
United States	7.4
Rest of the world**	14.3
World	**16.4**

2006 data

**Excludes countries with no hydro production

5.4.2 Deployment: Regional Aspects (organizations)

Figure 5.14 indicates that despite the significant growth of hydroelectric production, the percentage share of hydroelectricity fell in the last three decades (1973-2006). The major boom in electricity generation has been occurring due to the greater use of gas, and the greater participation of nuclear plants. Coal continues play a major role in the electricity matrix, with a small percentage growth in the 1973-2006 periods, growing from 38.3% to 41%.

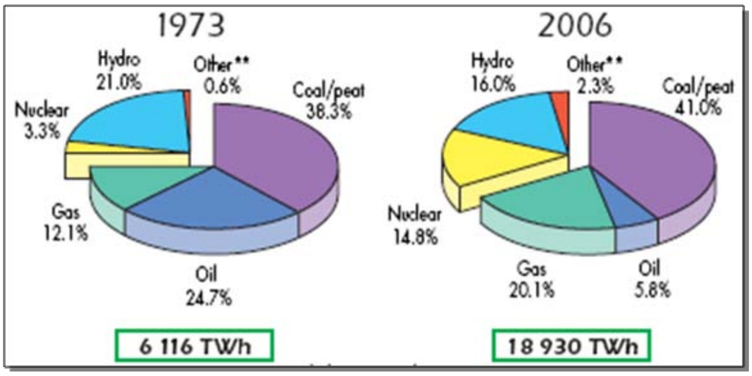


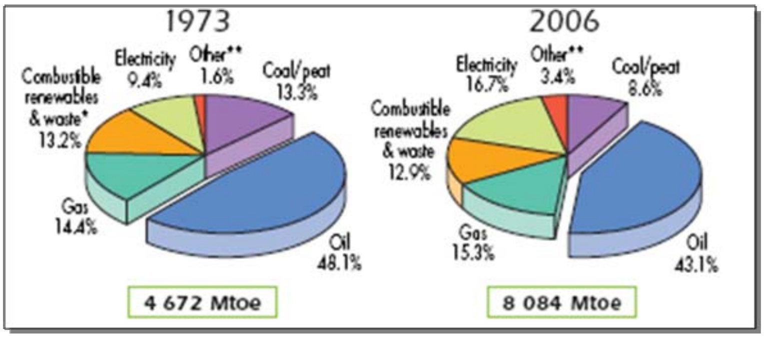
Figure 5.14: 1973 and 2006 fuel share of electricity generation* (Source: IEA, 2008).

Of the world's five major hydroelectricity producers (China, Canada, Brazil, the United States and Russia), only the United States is listed as one of the ten major producers of electricity (consistently amongst the top 3) using the three fossil fuels, namely coal, combustible oil and gas. China heads the list of producers of electricity from coal, followed by the United States. Russia stands out, in terms of production of electricity from gas, producing 55% in relation to the leader, the United States. The generation of electricity from combustible oil is relatively low-scale when compared with other combustible fuels: accounting for less than one third of the amount generated from the use of gas and around 14% of that generated using coal. In the use of combustible fuel for electricity generation, Japan is prominent, followed by Saudi Arabia. Brazil and Canada, on the other hand, do not appear on the list of the 10 major producers of electricity using these sources (coal combustible oil and gas).

Electricity is considered to be one of the most efficient energy carriers given the relative ease with which it can be transported and converted for use. In 2006, of the 8,084 billion toe of final consumption, approximately 16.7% was served by electricity, derived principally from fossil fuels (IEA, 2008).

The fact that electricity accounts for the major share of final consumption in 2006 (Figure 5.15) is due to the increase in the final consumption of electricity in China where there was a major acceleration in the generation of electricity, principally during the last decade (Figure 5.16).

In 1973, China represented 2.8% of the worldwide generation of electricity, but by 2006, its share had grown over fivefold, accounting for 15.3% (IEA, 2008).



** Other includes geothermal, solar, wind, heat, etc.

Figure 5.15: 1973 and 2006 fuel share of total final consumption (Source: IEA, 2008).

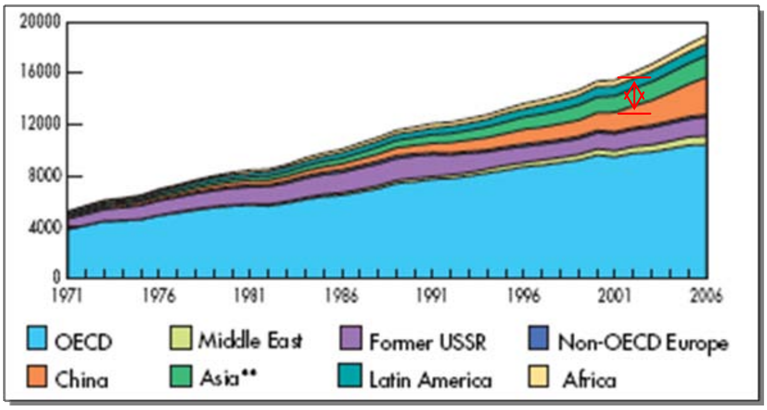


Figure 5.16: Evolution from 1971 to 2006 of world electricity generation* by region (TWh) 'Key World Energy Statistics'. (Source: IEA, 2008).

5.4.3 Industry Status

5.4.3.1 Relevant technical development

With hydropower technology, the challenge is to improve by continuously pushing the envelope in terms of operational range (head and discharge), environmental performance, materials, efficiency and costs. Effort is also being made to develop equipment to operate with even greater flexibility and in more difficult conditions/constraints. Low head and fish friendly turbines are recent technical developments.

Strategic planning and assessment is needed to optimize benefits and minimize impacts. The least-cost option for producers desiring additional capacity is almost always to modernize existing plants, whenever possible. Equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Innovations of Hydro industry are further elaborated subsequently in section 5.7.1.

5.4.4 Role of Hydropower in the Present Energy Markets (flexibility)

The primary role of hydropower is electricity generation. Hydro power plants can operate in isolation and supply independent systems, but most are connected to a transmission network. Hydroelectricity is also used for space heating and cooling in several regions. Most recently hydro electricity has also been used in the electrolysis process for hydrogen fuel production. Hydropower can also provide the firming capacity for wind power. By storing potential energy in reservoirs, the inherent intermittent supply from wind power schemes can be supported. Peak power is expensive. Thus, in both a regulated or deregulated market hydropower plays a major role and provides an excellent opportunity for investment.

Hydro generation can also be managed to provide ancillary services such as voltage regulation and frequency control. With recent advances in 'variable-speed' technology, these services can even be provided in the pumping mode of reversible turbines.

5.4.5 Carbon credit market

Hydropower projects are one of the main contributors to carbon credits. There are two methodologies approved by UNFCCC that can be used for hydropower projects according to their size: AMS ID for small scale projects (less than 15 MW) and ACM002 for large scale projects (above 15 MW). 1163 hydropower projects in the CDM pipeline represent 26% of the total CDM projects. The CDM Executive board have decided that Storage Hydropower projects will have to follow the power density indicator, W/m2 (Installed effect on inundated area). However, this indicator treats all reservoirs as equal whether they are in cold climates or not and regardless of amount and sources of carbon in the reservoir. The power density rule seems presently to exclude storage hydropower based on assumptions and not scientific or professional documentation. The issue of methane production from reservoirs are discussed later in this chapter.

Out of the 1300 projects registered by the CDM Executive Board by January 1st 2009, 287 are hydropower projects (See figure 5.17) [TSU: Reference to Figure 5.17 not clear here; should probably be moved to above paragraph; also numbers given should be checked]. When considering the PDD-predicted volumes of CERs to be delivered, registered hydro projects are expected to generate around 20 million tonnes per year, equivalent to 8% of the total

The majority of hydropower projects in the pipeline are at the validation stage, with 60% at this early stage of the process. A significant portion of these projects are based in China (67%), India (9%) and Brazil (6%). (See Figure 5.18). So far only 12 projects have been rejected by the CDM Executive Board on the grounds of not having additionality criterion.

Large hydro projects are coming more and more through the system. In Europe the Linking Directive allows a fixed amount of CERs to be brought into the EU Emission Trading Scheme (ETS, the biggest CO_2 market in the World) and this Directive sets conditions on the use of such credits. For hydropower projects of 20 MW capacities and above Member States must “ensure that relevant international criteria and guidelines, including those contained in the World Commission on Dams Report (see section 5.6.2) will be respected during the development of such project activity”. However Member States have interpreted this Directive in different ways because this Report is not specific for implementation (see section 5.6.2 on Existing Guidelines and Regulation of this chapter). This has led to European carbon exchanges (European Climate Exchange, Nord Pool etc) refusing to offer such credits for trade on their platforms, as it is not clear whether they are fully fungible. The European Union has therefore initiated a process to harmonize this procedure so as to give the market and the Member States confidence when using and accepting carbon credits under the EU ETS.

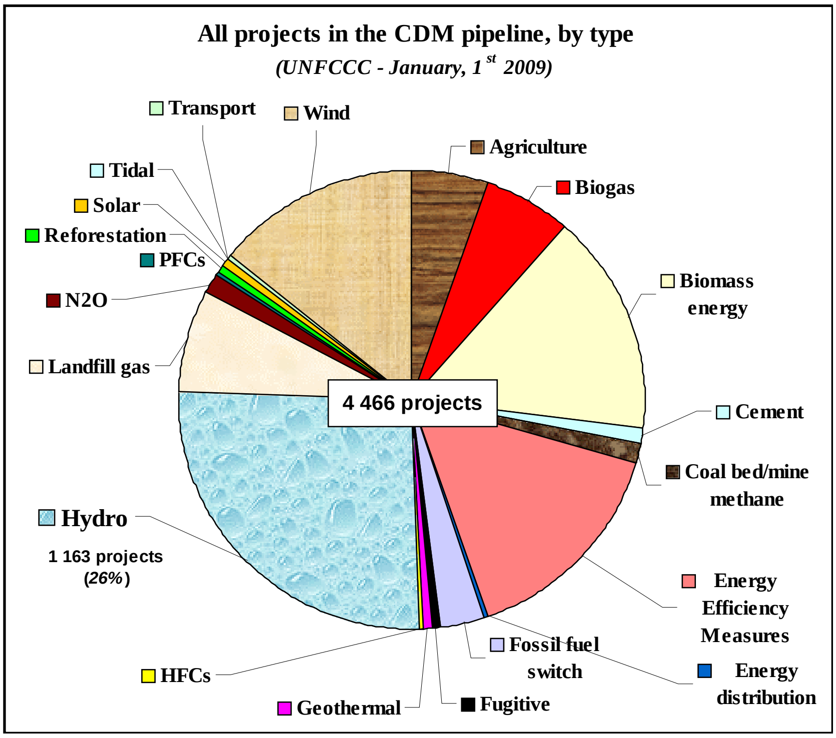


Figure 5.17: Hydro share in the CDM pipeline January, 1st 2009 (Source: UNFCCC): a type analysis.

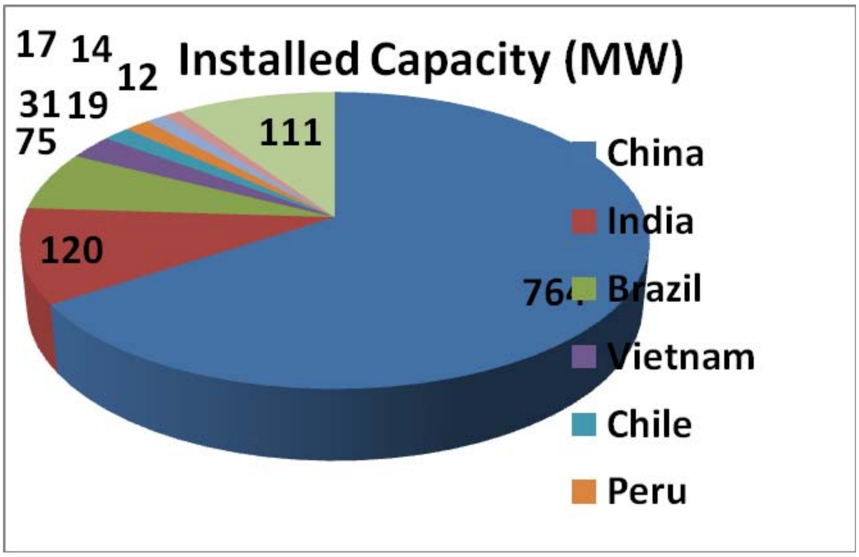


Figure 5.18: Country wise Hydropower projects registered for CDM as on January, 1st 2009 (source UNFCCC).

Carbon credits benefit hydro projects helping to secure financing and to reduce risks. Financing is a most decisive step in the entire project development. Therefore additional funding from carbon credit markets could be a significant financial contribution to project development (increase in return on equity and improve internal rate of return) which can be observed in several ways: 1) additional revenues from the credits, and 2) higher project status as a result of CDM designation (enhanced project's attractiveness for both equity investors and lenders).

5.4.6 Removing barriers to hydropower development

As with any energy source, the choice of hydroelectricity represents physical action and impacts, with inevitable modification of the environmental conditions and the ecological system. The recurring challenge of this option is to minimize the environmental and social aspects relating to its considerable scale gains, whilst at the same time broadening the multiplying effects of investment in infra-structure, stimulating the economy and engendering local research and technological development.

This option requires a large volume of initial resources for the project, contrary to thermal and gas/oil/coal options which require fewer resources initially, but which have higher operational costs and a greater level of pollution emissions. Allied to greater initial costs and longer time necessary to reach the operational stage, hydroelectric projects tend to be more exposed to regulatory risks, particularly in developing countries where there are regulatory lacunae which lead to higher risk premiums for private investors. Such lacunae include, for example: lack of definition in relation to the use of the land of indigenous peoples or conservation units.

At the same time, environmental issues have been assuming greater significance in the analysis of hydroelectric plants, both from the standpoint of multilateral supply agents or from civil society which is more organized, aware and demanding in relation to the impacts and inherent benefits of multiple use of water resources.

The challenges, which, naturally, are not limited to those referred to above, must be addressed and met by public policies bearing in mind the need for an appropriate environment for investment, a stable regulatory framework, incentive for research and technological development and the provision of credit for the hydroelectricity option.

5.4.6.1 Financing

Many economically feasible hydropower projects are financially challenged. High up-front costs are a deterrent for investment. Also, hydro tends to have lengthy lead times for planning, permitting, and construction. The operating life of a reservoir is normally expected to be in excess of 100 years. Equipment modernization would be expected every 30 to 40 years. In the evaluation of life-cycle costs, hydro often has the best performance, with annual operating costs being a fraction of the capital investment and the energy pay-back ratio being extremely favorable because of the longevity of the power plant components (Taylor, 2008).

The energy payback is the ratio of total energy produced during that system's normal lifespan to the energy required to build, maintain and fuel the system (Fig 5.19). A high ratio indicates good performance. If a system has a payback ratio of between 1 and 1.5, it consumes nearly as much energy as it generates (Gagnon, 2008).

The development of more appropriate financing models is a major challenge for the hydro sector, as is finding the optimum roles for the public and private sectors.

The main challenges for hydro relate to creating private-sector confidence and reducing risk, especially prior to project permitting. Green markets and trading in emissions reductions will undoubtedly give incentives. Also, in developing regions, such as Africa, interconnection between countries and the formation of power pools is building investor confidence in these emerging markets. Feasibility and impact assessments carried out by the public sector, prior to developer tendering, will ensure greater private-sector interest in future projects (Taylor, 2008).

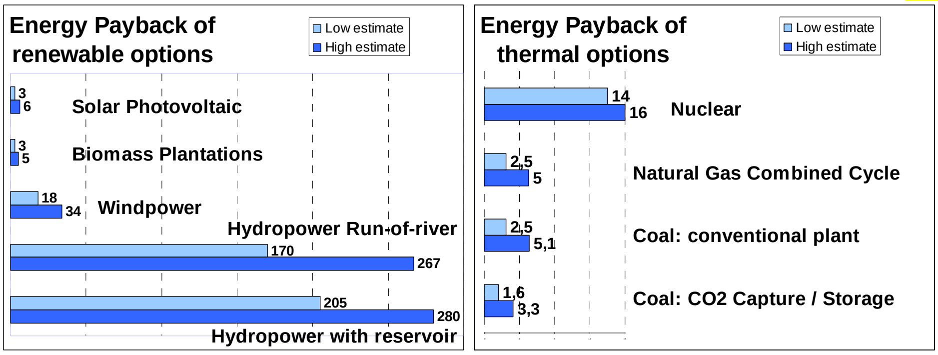


Figure 5.19: Energy Pay back Ratio (Source: Gagnon, 2008).

5.4.6.2 Administrative and Licensing process

The European Union differentiates between small and large hydropower. There are different incentives used for small hydro[2] (feed-in tariffs, green certificates and bonus) depending on the country, but no incentives are used for large hydro. For instance, France currently applies a legislation which provides a financial support scheme for renewable energy based on feed-in tariffs (FIT) for power generation. For renewable energy installations up to 12 MW, tariffs depend on source type and may include a bonus for some sources (rates are corrected for inflation). For hydro the tariff duration is 20 years, and the FIT is 60.7 €/MWh, plus 5 to 25 €/MWh for small installations, plus up to 16.8 €/MWh bonus in winter for regular production.

In France, under the law of 16 October 1919 on the use of hydropower potential, any entity wishing to produce electricity from water over and above 4.5 MW must be granted a specific concession by the French State. Power plants producing less than this capacity threshold are subject to a more flexible authorisation regime. Under this specific applicable regime, a concession can be granted for

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[2] In European Union, the limit for small hydro is 1.5 MW, 10 MW, 12 MW, 15 MW or 20 MW, depending on the country.

a maximum period of 75 years. The ownership of any installations constructed by the concession holder on the site is transferred to the State when the concession terminates. Also, these installations must be in a good order and free of any duties or rights, and this in effect imposes upon the concession holder a "custody obligation" to maintain the facilities in good working order throughout the term of the concession. Therefore the existing hydroelectric concessions in France will be opened to competition when they come up for renewal (the first call for bids is scheduled to take place in 2009). Similar arrangements may be seen in many countries

5.5 Integration into broader energy systems

Electricity markets and transmission systems have developed over the years to link large, ‘centralised’ power stations, producing firm power from fossil fuels, nuclear power and hydropower. The integration of electricity from ‘new’ renewable energy sources such as wind energy, solar and tidal wave energy therefore represents a degree of departure from the traditional pattern. The variability of electricity output from certain renewable energy technologies will, at a significant production share, necessitate changes in market and power system design, planning and communications, to ensure balance of supply and demand. Although large wind farms may be connected to medium, high or very high voltage networks, some new RES generation is connected to lower voltage distribution networks. The integration of hydropower into transmission systems should be seen in the perspective of the potential it represents for increasing the output of power systems and also smoothing the output from variable output technologies. Through integrated strategies, hydropower can buffer fluctuations in wind power, increasing the economic value of the power delivered (US DOE 2003). Likewise, wind energy can provide hydropower operators with additional flexibility in managing their water resources.

5.5.1 Contribute to less GHG from thermal by allowing steady state operation

Hydro power plants are extremely quick response to intermittent loads as they can be brought on stream within a short period and their outputs can be varied almost instantaneously to respond to varying loads. Thermal power plants (coal, gas or liquid fuel) on the other hand require considerable lead times (4 hours for gas plants and over 8 hours for steam plants) before they attain the optimum thermal efficiency state when the emission per unit output is minimum. In an integrated system, the hydro power plant is used as the peaking plant; the thermal units are used as base loads thus ensuring maximum thermal efficiency and lower emissions per output.

5.5.2 Grid/independent applications (isolated grids, captive power plants)

Hydropower can be served through national and regional electric grid, mini grid and also in isolated mode. There are several hydro projects which are for captive use and have been since very beginning of hydropower development. Water mills in England and many other parts of the world, for grinding the cereals, for water lifting and for textile industry are the early instances where hydropower has been used as captive power in mechanical as well as electrical form (See Figure 5.20). The tea and coffee plantation industry have used and still are using hydropower for their captive needs in isolated areas. In the era of electricity deregulation which allows open access to the grid, people are encouraged to install hydropower plants and use the electricity for captive purpose by industry or individual or group of individuals.

Figure 5.20: 200 kW isolated hydropower plant in Dewata Tea Estate, Indonesia.

On the other hand rural areas may not have grids due to economic reasons and mini grid or isolated systems based hydropower may be economically justified. Depending upon power availability and demand there are mini or local grids where hydropower (especially small hydro power) is used. These mini grids often work as isolated grids.

Hydropower plants are good investment opportunity as captive power house for industry and municipal bodies. The captive power plants may work in isolation through local, regional and national grids.

Isolated grid often faces the problem of poor plant load factor and making financial return difficult for the plant. But this provides opportunities for the area to have industry expansion, cottage or small industry, irrigation pumping, drinking water, agriculture and other application, education and entertainment activity for the overall development of the area.

5.5.3 Rural electrification

Nearly two billion people in rural areas of developing countries do not have electricity (Table 5.3). They use kerosene or wood to light their homes. Their health is damaged by the smoke given off by these fuels. The problems of rural energy have long been recognized. Without electricity, moreover, poor households are denied a host of modern services such as electric lighting, fans, entertainment, education, health care and power for income generating activities.

The access to affordable and reliable energy services will contribute and will help in alleviation of illiteracy, hunger and thirst, disease, uncontrolled demographic proliferation, migration etc as well as improvement of the economic growth prospects of developing countries.

Extending an electricity grid to a remote village can be quite expensive and a challenge for a power utility. Renewable energy such as solar, wind, and small hydropower are often ideal to provide electricity in rural areas. There has been a growing realisation in developing countries that small hydro schemes have an important role to play in the economic development of remote rural areas, especially hilly areas. Small hydro plants can provide power for industrial, agricultural and domestic uses both through direct mechanical power or producing electricity. Small hydropower based rural electrification in China has been one of the most successful examples, building over 45,000 small hydro plants of 50,000 MW and producing 150 Billion kWh annually, and accounting for one third of country’s total hydropower capacity, covering its half territory and one third of counties and benefitting over 300 Million people (up to 2007) (SHP News 2008).

Table 5.3: Electricity Access in 2005; Regional Aggregates.

Region	**Population** Million	**Urban population** Million	**Population without electricity** Million	**Population with electricity** Million	**Electrification rate** %	**Urban electrification rate** %	**Rural electrification rate** %
Africa	891	343	554	337	37.8	67.9	19.0
North Africa	153	82	7	146	95.5	98.7	91.8
Sub-Saharan Africa	738	261	547	194	25.9	58.3	8.0
Developing Asia	3418	1063	930	2488	72.8	86.4	65.1
China and East Asia	1951	772	224	1728	88.5	94.9	84.0
South Asia	1467	291	706	760	51.8	69.7	44.7
Latin America	449	338	45	404	90.0	98.0	65.6
Middle East	186	121	41	145	78.1	86.7	61.8
Developing Countries	**4943**	**1866**	**1569**	**3374**	**68.3**	**85.2**	**56.4**
Transition economies and OECD	**1510**	**1090**	**8**	**1501**	**99.5**	**100.0**	**98.1**
World	**6452**	**2956**	**1577**	**4875**	**75.6**	**90.4**	**61.7**

Source: Energy Outlook 2006

Small hydro is one of the best options for rural electrification which can offer considerable financial benefits to the individual as well as communities served. Even though the scale of small hydro capital cost may not be comparable with large hydropower several cost aspects associated with large hydropower schemes justify the small hydropower development due to their dispersed location and opportunity advantage.

- Normally small hydro are RoR schemes
- Locally/small factories manufactured equipment may be used
- Electronic load controller – allows the power plant to be left unattended, thereby reducing manpower costs
- Using existing infrastructure such as dams or canal fall on irrigation schemes
- Locating close to villages avoid expensive high voltage distribution equipment
- Using pumps as turbines and motors as generators as a turbine/generator set
- Use of local materials for the civil works
- Use of community labour

Development of small hydropower for rural areas involves social, technical and economic aspects. Local management, ownership and community participation, technology transfer and capacity building are the basic issues for success of small hydro plants in rural areas.

5.5.4 Hydropower peaking

Demands for power vary greatly during the day and night, during the week and seasonally. For example, the highest peaks are usually found during summer daylight hours when air conditioners are running in a warm climate. In northern regions the highest peak hours are usually found in the morning and in the afternoon during the coldest periods in the winter.

Nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods. Their operational requirements and their long startup times make them more efficient for meeting base load needs only. Since hydroelectric generators can be started or stopped almost instantly, hydropower is more responsive than most other energy sources for meeting peak demands. Water can be stored overnight in a reservoir until needed during the day, and then released through turbines to generate power to help supply the peak load demand. This mixing of power sources offers a utility company the flexibility to operate steam plants most efficiently as base plants while meeting peak needs with the help of hydropower. This technique can help ensure reliable supplies and may help eliminate brownouts and blackouts caused by partial or total power failures.

Increasing use of other types of energy-producing power plants in the future will not make hydroelectric power plants obsolete or unnecessary. On the contrary, hydropower shall be even more important. While nuclear or fossil-fuel power plants can provide base loads, hydroelectric power plants can deal more economically with varying peak load demands in addition to delivering base load.

Like peaking, pumped storage keeps water in reserve for peak period power demands. Pumped storage is water pumped to a storage pool above the power plant at a time when customer demand for energy is low, such as during the middle of the night. The water is then allowed to flow back through the turbine-generators at times when demand is high and a heavy load is placed on the system. The reservoir acts much like a battery, storing power in the form of water when demands are low and producing maximum power during daily and seasonal peak periods. An advantage of pumped storage is that hydroelectric generating units are able to start up quickly and make rapid adjustments in output. They operate efficiently when used for one hour or several hours.

Intermittent energy sources like solar power and wind power may be tied to pumped storage hydro power systems to be economical and feasible. Hydropower can serve as an instant backup and to meet peak demands. Wind power can be used when the wind is blowing, to reduce demands on hydropower. That would allow dams to save their water for later release to generate power in peak periods.

Hydropower is important from an operational standpoint as it needs no "ramp-up" time, as many combustion technologies do. Hydropower can increase or decrease the amount of power it is supplying to the system almost instantly to meet shifting demand. With this important load-following capability, peaking capacity and voltage stability attributes, hydropower plays a significant part in ensuring reliable electricity service and in meeting customer needs in a market driven industry. In addition, hydroelectric pumped storage facilities are the only significant way currently available to store large amounts of electricity. Hydropower’s ability to provide peaking power, load following, and frequency control helps protect against system failures that could lead to the damage of equipment and even brown or blackouts (US Department of Interior, 2005).

5.5.5 Energy storage (in reservoirs)

Hydroelectric generation differs from other types of generation in that the quantity of “fuel” (i.e. water) that is available at any given time is fixed. This unique property allows hydropower plants to be used as storage reservoirs. Techniques such as seasonal/multi seasonal storage or daily/weekly pondage can be used in many cases to make the distribution of stream flow better suitable to the power demand pattern. Hydro with its short response time is well suited for peaking or load-following operation and is generally used for this service if storage or pondage is available and if river conditions permit.

Reservoir based hydropower store kinetic energy as a potential for electricity production. This is the main storage aspect of hydropower. An example of scale is how Scandinavian hydropower through their reservoirs back up and regulate wind power in Denmark/Germany and also deliver peak production via cables to Europe (ref also chapter 8). Norwegian hydropower alone represent approximate half the total reservoir capacity in Europe. Storing of water is considered storage of energy and can be loosely termed as batteries for the power system. It should be emphasized that while hydropower reservoirs store energy as a source for electricity before it is produced, pumped storage plants store electricity after it is produced.

Electricity already produced cannot be stored directly except by means of small capacitors and hence is to be stored in other forms, such as chemical (batteries or on a large scale in Flow Batteries), potential energy (pumped storage) or mechanical energy as compressed air (CAES, compressed air energy storage) or flywheels. For large scale energy storage only potential energy through pumped storage schemes are presently viable. Various technologies for storing electricity in the grid are compared in figure 5.21. CAES systems are not shown. CAES can store a substantial amount of energy.

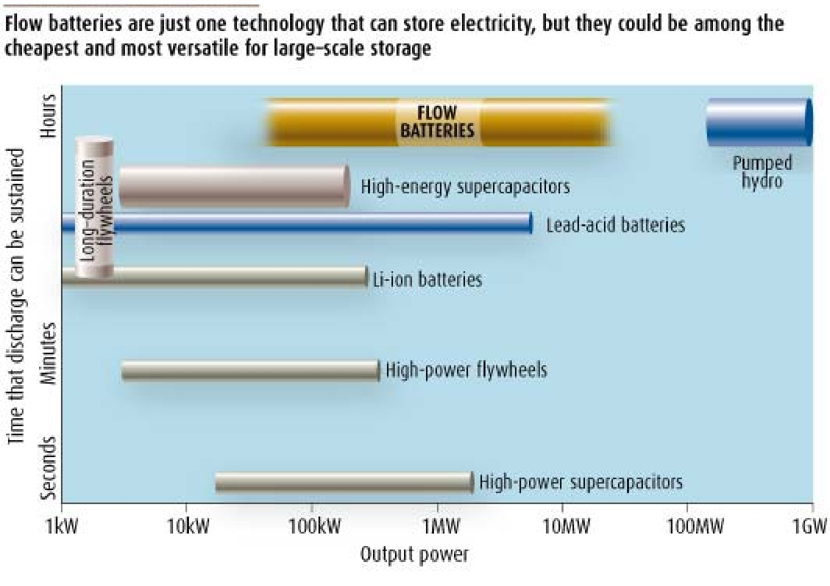
Flow batteries are just one technology that can store electricity, but they could be among the cheapest and most versatile for large-scale storage

Figure 5.21: Pumped Storage ability to store electricity compared with various technologies (Source: Thwaites, 2007).

Pumped storage hydroelectricity is used by some power plants for *load balancing*. The method stores energy by pumping water from a low to a higher elevation. Low-cost off-peak electric power is used to run the pumps. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of *peak demand*, when electricity prices are highest. Pumped storage is the largest-capacity form of grid energy storage now available.

The main components of a pumped storage project are the upper and lower reservoirs, water conductor, a power house with reversible pump/turbine motor/generators and a high voltage transmission connection. The hydraulic, mechanical and electrical efficiencies determine the overall cycle efficiency. The overall cycle efficiency of pumped storage plants ranges from 65 to 80 per cent.

Conventional pumped storage projects are often constructed in conjunction with large base-load generating stations such as nuclear and coal fired stations (- or may be an integral part of a large storage HPP). The pumped storage plant complements the large base load plant by providing guaranteed load during early morning hours when system demand is low. Pumped storage is also desired, in the case of nuclear plants, providing frequency control and reserve generation required maintaining operation of critical cooling pumps. Estimates of the ideal mix of electricity storage and conventional power generation suggest that pumped storage should amount to 6 to 8 % of the total power generation capacity.

The most common type of pure pumped storage is the off-stream configuration. The off-stream configuration consists of a lower reservoir on a stream, river or other water source, and a reservoir located off-stream usually at a higher elevation. It is possible to construct an off-stream pumped storage project in which the off-stream reservoir is at a lower elevation such as an abandoned mine or underground cavern.

Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydropower plants, can also respond to load changes within seconds.

Grid energy storage lets energy producers transmit excess electricity over the electricity transmission grid to temporary electricity storage sites from where electricity may be transmitted to the places when needed. Grid energy storage is particularly important in matching supply and demand over a 24 hour period of time.

5.5.6 Supply characteristics

Electricity markets and transmission systems have developed over the years to link large, ‘centralised’ power stations, producing firm power from fossil fuels, nuclear power and hydropower. The hydropower is a traditional power source and operates in all integrated grid systems.

The large-scale, worldwide, development of hydroelectric energy, aside from its low cost, is due to the excellent characteristics of energy supply for the power system. It is common to have machine availability percentages that are over 95% at a hydroelectric plant. The most important characteristic is the storage capacity that hydroelectric energy can offer the electric system and the speed the hydraulic machines offer in following the electric demand. The hydroelectric plants usually offer an auxiliary service called Automatic Generation Control or AGC. Power plants that use combustion processes in the transformation of energy (thermal cycle), are not as fast in their time response when faced with sudden and important variations in demand, as there exists a risk of damage to their components by thermal stress.

The optimizing exercise for a hydroelectric power plant is based on the size of the units and the available power, at a specific site. The project's final costs are reduced when the size of the units to be installed is large. This also represents an advantage for the electrical power system, because the large power units provide stability to the electric grid. A hydroelectric plant with large machines (> 50 MW) is desirable in order to provide black start service, which is indispensable in any electrical power system.

We can conclude that the energy supply characteristics of hydroelectric plants make it indispensable in the development energy matrix of any electric system, aside from the collateral advantages such as providing water reserves for human, agricultural and industrial development.

5.5.6.1 Electrical services and use factors

The net capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its output if it had operated at full rated capacity the entire time. A hydroelectric plant's production may also be affected by requirements to keep the water level from getting too high or low and to provide water for fish downstream or for navigation upstream. When hydroelectric plants have water available, they are also useful for load following, because of their high *dispatchability*. A typical hydroelectric plant's operators can bring it from a stopped condition to full power in just a few minutes.

Example of representative international statistics can be found in table 5.4.

Table 5.4: AVAILABILITY INDEXES NERC 2000 - 2004.

Technology	Number Of Units (Sample)	Service Time (Years)	NCF	AF	FOF	FOR	EFOR
Hydro	1179	53	40.8	89.4	2.50	3.70	3.75
Thermal Oil (1-99 MW)	35	14	25.0	90.8	1.92	5.47	12.38
Thermal Coal (100-199 MW)	226	46	65.6	88.6	3.58	4.11	6.03
Gas Turbines (20-49 MW)	54	26	6.4	89.6	1.52	34.59	38.21
Gas Turbines (> 50 MW)	501	14	4.3	92.4	2.16	25.34	25.91
Diesel Engines	87	33	6.7	94.5	2.20	26.90	27.82
Notes:							
NCF	Plant Factor						
AF	Availability Factor (Available hours/hours of period)						
FOF	Forced Outage Factor (Hours of forced outage/hours of period)						
FOR	Forced Outage Rate ((hours of forced outage/hours of forced outage + hours of service)						
EFOR	Equivalent Forced Outage Factor (hours of equivalent forced outage/hours of equivalent forced outage + hours of service)						

5.5.6.2 Security

The subject of Energy Security in its broadest sense encompasses a wide range of issues, technologies and government policies. Energy Security (also known as System Security) involves the design of the system to provide service to the end user despite fuel availability problems, forced outages of generators and outages of transmission system components. Grids with hydro power plants into it can fulfil the Security requirement due to hydro storage on reservoirs.

5.5.6.3 Reliability/quality

Hydroelectric power is usually extremely dispatchable and more reliable than other renewable energy sources. Many dams can provide hundreds of megawatts within seconds of demand, the exact nature of the power availability depending on the type of plant. In run of river plants power availability is highly dependent on the uncontrollable flow of the river.

5.5.6.4 Ancillary services

Ancillary Service refers to a service, necessary to support the transmission of energy from resources to loads while maintaining reliable operation of the transmission system in accordance with Good Utility Practice. Such services include mainly: voltage control, operating reserves, black-start capability and frequency control.

Hydroelectric generators have technical advantages over other types of generation with respect to the supply of ancillary services (Altinbilek, 2007). The advantages include:

- Fast response
- Better part-load efficiency
- Better controllability
- Lower maintenance costs
- Minimum to no start up (unit commitments) costs

5.5.7 Regional cooperation

Availability and movement of water may cross political or administrative boundaries. There are 263 transboundary river basins and 33 nations have over 95 percent of their territory within international river basins. While most transboundary river basins are shared between two countries, this number is much higher in some river basins. Worldwide, thirteen river basins are shared between five to eight countries. Five river basins, namely the Congo, Niger, Nile, Rhine and Zambezi, are shared between nine to eleven countries. The Danube River flows through the territory of 18 countries which is the highest for any basin. Management of transboundary waters poses one of the most difficult and delicate problems. Vital nature of freshwater provides a powerful natural incentive for cooperation. Fears have been expressed that conflicts over water might be inevitable as water scarcity increases. International cooperation is required to ensure that the mutual benefits of a shared watercourse are maximized and optimal utilization of the water resources may play a key role in economic development.

One hundred twenty-four of the 145 treaties (86%) are bilateral. Twenty-one (14%) are multilateral; two of the multilateral treaties are unsigned agreements or drafts. Most treaties focus on hydropower and water supplies: fifty-seven (39%) treaties discuss hydroelectric generation and fifty-three (37%) distribute water for consumption. Nine (6%) mention industrial uses, six (4%) navigation, and six (4%) primarily discuss pollution. Thirteen of the 145 (9%) focus on flood control. Not surprisingly, mountainous nations at the headwaters of the world's rivers are signatories to the bulk of the hydropower agreements. Dispute on treaties are resolved through technical commissions, basin commissions, or via government officials.

There are opportunities for cooperation in transboundary water management which can help in building mutual respect, understanding and trust among countries and may promote peace, security and sustainable economic growth. The 1997 UN Convention on the Non-Navigational Uses of International Watercourses (1997 IWC Convention) is the only universal treaty dealing with the use of freshwater resources. Nepal alone has four treaties with India (the Kosi River agreements, 1954, 1966, 1978, and the Gandak Power Project, 1959) to exploit the huge power potential in the region. Itapúa Hydropower on river Parana in Brazil and Paraguay and Victoria Lake hydropower in Uganda, Tanzania and Kenya are some notable instances of regional cooperation.

5.5.8 Support to other renewables

Hydropower provides high degree of flexibility and reliability of its services and is a great opportunity to ensure the backup for a stable grid with intermittent renewable electricity sources, such as wind and sun. Hydropower plants and their reservoirs serve as a universal energy, power regulator. Hydropower plants with reservoirs work as energy storage and regulator to the other renewable and may be described as below**:**

- Hydro plants with reservoirs can lower or shut down their output when the wind turbines, or the solar panel, or the run-of-river hydro plants are able to provide their energy services;
- Hydropower plants can operate when intermittent power from other renewable or run of river is not available. Such service may be provided on an hourly, weekly, monthly, annual or inter-annual basis;
- It provides to the other renewable all the ancillary services;
- Hydropower plants with reservoirs are not affected on hourly, daily or weekly basis and thus are a good backbone to other renewable;
- Pumped storage and reservoir based hydro plants provided natural support to other renewable sources of energy;
- Reservoir based hydropower can complement continuous, base-load generation from geothermal schemes;
- “Peaking” biomass schemes can provide backup to run of river hydro schemes.

5.6 Environmental and social impacts

Like all other energy and water management options, hydropower projects do have up and downsides. On the environmental side, hydropower offers advantages on the macro-ecological level, but shows a significant environmental foot print on the local and regional level. With respect to social impacts, a hydropower scheme will often be a driving force for socio-economic development (see sub-section 5.6.4), yet a critical question remains on how these benefits are shared.

Moreover, each hydropower plant (HPP) is a unique product tailored to the specific characteristics of a given geographical site and the surrounding society and environment. Consequently, the magnitude of environmental and social impacts as well as the extent of their positive and negative effects is rather site dependent. For this reason the mere size of a HPP is not a relevant criterion to anticipate impacts. Nevertheless, sub-section 5.6.1 hereafter attempts to summarize the main environmental and social impacts which can be created by the development of the various types of hydropower projects, as well as a number of practicable mitigation measures which can be implemented to minimize negative effects and maximize positive outcomes. More information about existing guidance for sustainable hydropower development is provided in sub-section 5.6.2.

One of hydropower’s main environmental advantages is that it creates no atmospheric pollutants or waste. Over its life cycle, a HPP generally emits much less CO_2 than most other sources of electricity, as described in sub-section 5.6.3 hereafter. In some cases, reservoirs absorb more GHG than they emit. However, under certain conditions[3] some reservoirs may emit methane (CH_4). Thus, there is a need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. Sub-section 5.6.3 also aims at recapitulating current scientific knowledge about these particular circumstances.

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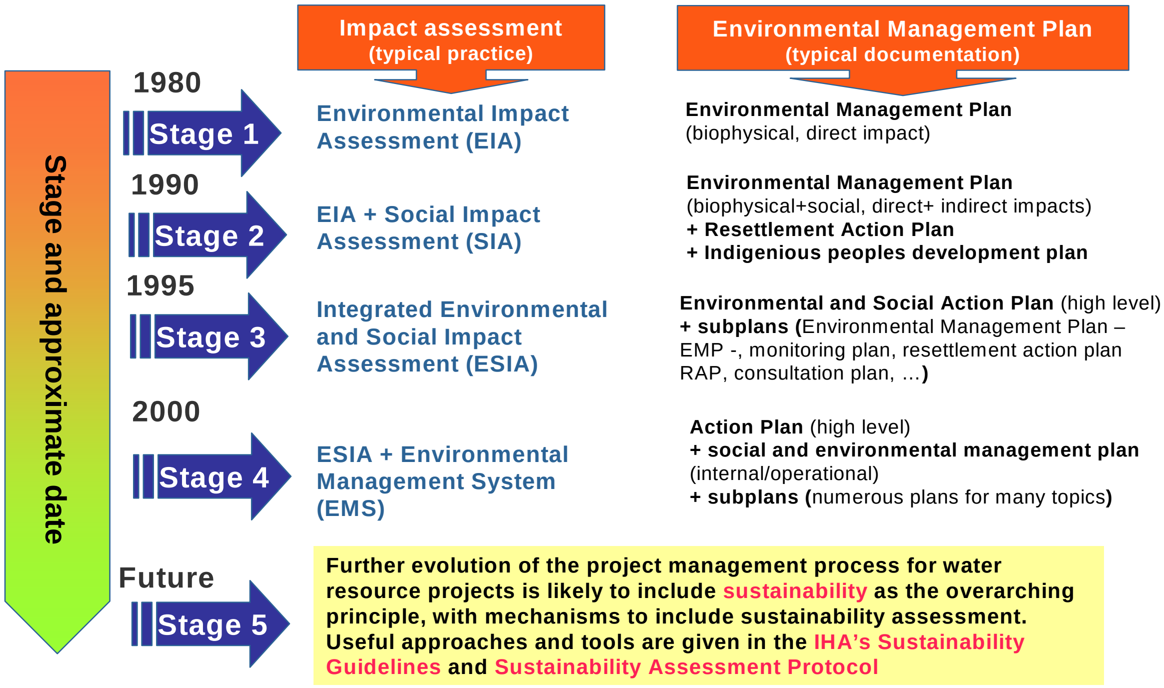
[3] Climate, temperature, inundated biomass, topography, water residence time, oxygen level, etc.

Furthermore, throughout the past decades project planning has evolved acknowledging a paradigm shift from a technocratic approach to a participative one (Healey, 1992). Nowadays, stakeholder consultation has become an essential tool to improve project outcomes. It is therefore important to identify key stakeholders[4] early in the development process in order to ensure positive and constructive consultations. Emphasizing transparency and an open, participatory decision-making process, this new approach is driving both present day and future hydropower projects toward increasingly more environment-friendly and sustainable solutions. At the same time, the concept and scope of environmental and social management associated with hydropower development and operation have changed moving from a mere impact assessment process to a global management plan encompassing all sustainability aspects. This evolution is described in more details in Figure 5.22.

5.6.1 Typical impacts and possible mitigation measures

Although the type and magnitude of the impacts will vary from project to project, it is possible to describe some typical effects, along with the experience which has been gained throughout the past decades in managing and solving problems. Though some impacts are unavoidable, they can be minimized or compensated as experience in successful mitigation demonstrates. There are now a number of “good practice” projects where environmental and social challenges were handled successfully[5] (IEA, 2000a; UNEP, 2007). By far the most effective measure is impact avoidance, weeding out less sustainable alternatives early in the design stage.



Further evolution of the project management process for water resource projects is likely to include sustainability as the overarching principle, with mechanisms to include sustainability assessment. Useful approaches and tools are given in the IHA’s Sustainability Guidelines and Sustainability Assessment Protocol

Figure 5.22: Evolution of the E&S process, adopted from UNEP (2007).

HPP can be an opportunity for better protecting existing ecosystems. Some hydropower reservoirs have even been recognized as new, high-value ecosystems by being registered as “Ramsar” reservoirs (Ramsar List of Wetlands of International Importance, 2009). At the same time, HPPs modify aquatic and riparian ecosystems, which can have significant adverse effects according to the project’s specific site conditions. Altered flow regimes, erosion and heavily impacted littoral zones

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[4] Local/national/regional authorities, affected population, NGOs, etc.

[5] a) IEA/IHASustainable Hydopower Website at www. sustainablehydropower.org

in reservoirs are well known types of negative impacts (Helland-Hansen et.al. 2005). Yet, in some cases the effect on the river system may also be positive. Recent investigations from Norway in the regulated river Orkla have shown an increase in the salmon production caused by the flow regulating effect of hydropower schemes which increases winter flows and protects the roe and young fish from freezing (net increase in smolt production after the hydropower development of 10-30% (Hvidsten, 2004)This was also supported by LAbée-Lund *et al.* (L'Abée-Lund *et al.*, 2006) who compared 22 Norwegian rivers, both regulated and not-regulated, based on 128 years of catch statistics. For the regulated rivers they observed no significant effect of hydropower development on the annual catch of anadromous salmonids. For two of the regulated rivers the effect was positive. In addition enhancement measures such as stocking and building fish ladders significantly increased annual catches A review (Bain, 2007) looking at several hydropower peaking cases in North-America and Europe indicates clearly that the impacts from HPPs in the operational phase is variable, but in many cases has a positive effect on downstream areas. Dams can namely be a tool to improve the following ecological services: management of water quantity and quality, ground water stabilization in adjacent areas, preservation of wetlands, control of invasive species, sediment management.

With respect to social impacts, HPPs are generating revenues from a natural and domestic resource, a river. As documented by Scudder (Scudder, 2005), they may have positive impacts on the living conditions of local communities and the regional economy. Thus on the positive side, a hydropower often fosters socio-economic development, not only by generating electricity but also by facilitating through the creating of freshwater storage schemes multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. Yet, inevitably questions arise about the sharing of these revenues among the local affected communities, government, investors and the operator. Key challenges in this domain are the fair treatment of affected communities and especially vulnerable groups like indigenous people, resettlement if necessary and public health issues, as well as appropriate management of cultural heritage values.

According to hydropower-specific studies realised over a ten year period by the IEA (2000b; 2006), eleven sensitive issues have been identified that need to be carefully assessed and managed to achieve sustainable hydropower projects:

5.6.1.1 Hydrological Regimes

Depending on the type of hydropower project, the river flow regime is more or less modified. Run-of-river projects can use all the river flow or only a fraction of it, but leave the river’s flow pattern essentially unchanged, reducing downstream impacts of the project. HPPs with reservoirs alter significantly the hydrological cycle downstream, both in terms of frequency and volume of flow discharge. Some projects involve river diversions that may modify the hydrological cycle along the diversion routes. Physical and biological changes are related to variations in water level. The magnitude of these changes can be mitigated by proper power plant operation and discharge management, regulating ponds, information and warning systems as well as access limitations. There is also a trend to incorporate ecological minimum flow considerations into the operation of water control structures as well as increasing needs for flood and drought control. Major changes in the flow regime may entail modifications in the estuary, where the extent of salt water intrusion depends on the freshwater discharge. Another impact associated with dam construction is decreased sediment loading to river deltas. A thorough flow management program can ensure to prevent loss of habitats and resources. Further possible mitigation measures might be to release controlled floods in critical periods and to build weirs in order to maintain water levels in rivers with reduced flow or to prevent salt intrusion from the estuary.

5.6.1.2 Reservoir Creation

Although not all HPPs do have a reservoir, it is the impoundment of land which has the most important adverse impacts, while the thus created new freshwater and renewable energy storage capacity is also providing the most benefits to society, as it helps to manage water quantity and balance fluctuations in the electricity supply system. Creating a reservoir entails not only the transformation of a terrestrial ecosystem into an aquatic one, it also brings along important modifications to river flow regimes by transforming a relatively fast flowing water course into a still standing water body. For this reason, the most suitable site for a reservoir needs to be thoroughly studied, as the most effective impact avoidance action is to limit the extent of flooding on the basis of technical, economic, social and environmental considerations.

Generally, reservoirs are good habitat for fish. However, the impacts of reservoirs on fish species will only be perceived positively if species are of commercial value or appreciated for sport and subsistence fishing. If water quality proves to be inadequate, measures to enhance the quality of other water bodies for valued species should be considered in co-operation with affected communities. Other options to foster the development of fish communities and fisheries in and beyond the reservoir zone are for example to create spawning and rearing habitat, to install fish incubators, to introduce fish farming technologies, to stock fish species of commercial interest which are well adapted to reservoirs as long as this is compatible with the conservation of biodiversity within the reservoir and does not conflict with native species, to develop facilities for fish harvesting, processing and marketing, to build access roads ramps and landing areas or to cut trees prior to impoundment along navigation corridors and fishing sites, to provide navigation maps and charts and to recover floating debris.

As reservoirs take the place of terrestrial habitats, it is also important to protect and/or recreate the types of habitats lost through inundation. In general, long-term compensation and enhancement measures have turned out to be much more beneficial than the conservation of terrestrial habitats. Further possible mitigation measures might be to protect areas and wetlands that have an equivalent or better ecological value than the land lost, to preserve valuable land bordering the reservoir for ecological purposes and erosion prevention, to conserve flooded emerging forest in some areas for brood rearing waterfowl, to enhance habitat of reservoir islands for conservation purpose, to develop or enhance nesting areas for birds and nesting platforms for raptors or to practice selective wood cutting for herbivorous mammals as well as to implement wildlife rescue and management plans.

5.6.1.3 Water Quality

In some densely populated areas with rather poor water quality (e.g. Weser, Germany) run-of-river power plants are regularly used to improve oxygen levels and filter tons of floating waste (more than 1400 t/year) out of the river, or to reduce too high water temperature levels from thermal power generating outlets (Donau, Austria). However maintaining the water quality of reservoir is often a challenge, as reservoirs constitute a focal point for the river basin catchment. In cases where municipal, industrial and agricultural waste waters entering the reservoir are exacerbating water quality problems, it might be relevant that proponents and stakeholder cooperate in the context of an appropriate land and water use plan encompassing the whole catchment area, preventing for example excessive usage of fertilizers and pesticides. Most water quality problems, however, can be avoided or minimized through proper site selection and design, based on reservoir morphology and hydraulic characteristics. In this respect the two main objectives are to reduce the area flooded and to minimize water residence time in the reservoir. Selective or multi-level water intakes may limit the release of poor quality water in the downstream areas due to thermal stratification, turbidity and temperature changes both within and downstream of the reservoir. They may also reduce oxygen depletion and the volume of anoxic waters. The absence of oxygen can especially in warm climates contribute to the formation of methane in the first years after impoundment. Hence appropriate mitigation measures to prevent the formation of reservoir zones without oxygen also help to maintain the climate-friendly carbon footprint of hydropower (see 5.6.3 for more details). Some hydropower schemes have been successfully equipped with structures for re-oxygenation both in the reservoir (e.g. bubbling tubes, stirring devices) or downstream of the reservoir. Downstream gas super saturation may be mitigated by designing spillways, installing stilling basins or adding structures to favour degassing like aeration weirs. While some specialists recommend pre-impoundment clearing of the reservoir area, this must be carried out carefully because, in some cases, significant re-growth may occur prior to impoundment, and the massive and sudden release of nutrients may lead to algal blooms and water quality problems. In some situations “Fill and Flush”, prior to commercial operation, might contribute to water quality improvement, whereas planning periodic peak flows can increase aquatic weed drift and decrease suitable substrate for weed growth reducing problems with undesired invasive species. Increased water turbidity can be mitigated by protecting shorelines that are highly sensitive to erosion, or by managing flow regimes in a manner that reduces downstream erosion.

5.6.1.4 Sedimentation

In some countries like Norway or Canada, sedimentation is not an issue due to mainly hard, rocky underground. Yet, in areas with sandy or highly volcanic geology, or steep slopes, there is a natural predisposition for sedimentation which can be exacerbated by unsustainable land use in the river basin. Sedimentation has a direct influence on the maintenance costs and even on the feasibility of a HPP. The effect of sedimentation is not only reservoir storage capacity depletion over time due to sediment deposition, but also an increase in downstream degradation and increased flood risk upstream of the reservoirs. If significant reservoir sedimentation is unavoidable, appropriate attention must be paid during project planning to establish a storage volume that is compatible with the required life time of the project. Further possible actions to prevent reservoir sedimentation include careful site selection, determining precisely long-term sediment inflow characteristics to the reservoir, extracting coarse material from the riverbed, dredging sediment deposits, using special devices for sediment management like the installation of gated structures to flush sediment under flow conditions comparable to natural conditions, conveyance systems equipped with an adequate sediment excluder, sediment trapping devices or bypass facilities to divert floodwaters. Measures may also include agricultural soil (cover plants) or natural land (reforestation) protection in the catchment.

5.6.1.5 Biological Diversity

Whereas many natural habitats are successfully transformed for human purposes, the natural value of certain other areas is such that they must be used with great care or left untouched. The choice can be made to preserve natural environments that are deemed sensitive or exceptional. To maintain biological diversity, the following measures have proven to be successful: establishing protected areas; choosing a reservoir site that minimizes loss of ecosystems; managing invasive species through proper identification, education and eradication, conducting specific inventories to learn more about the fauna, flora and specific habitats within the studied area.

5.6.1.6 Barriers for Fish Migration and Navigation

Dams are creating obstacles for the movement of migratory fish species and for river navigation. They may reduce access to spawning grounds and rearing zones, leading to a decrease in migratory fish populations and fragmentation of non-migratory fish populations. However, natural waterfalls also constitute obstacles to upstream fish migration and river navigation. Those dams which are built on such waterfalls do therefore not constitute an additional barrier to passage. However HPPs which are located in rivers hosting migrating fish species can constitute an important threat to fish during downstream migrations. Most fish injuries or mortalities during downstream movement are due to their passage through turbines and spillways. Improvement in turbine design, spillway design or overflow design has proven to successfully minimize fish injury or mortality rates. More improvements may be obtained by adequate management of the power plant flow regime or through spillway openings during downstream movement of migratory species. Once the design of the main components (plant, spillway, overflow) has been optimized for fish passage, some avoidance systems may be installed (screens, strobe lights, acoustic cannons, electric fields, etc.), efficiency of which is highly site and species dependant, especially in large rivers. In some cases, it may be more useful to capture the fish in the headrace or upstream and release the individuals downstream. Other common devices include by-pass channels, fish elevators with attraction flow or leaders to guide fish to fish ladders and the installation of avoidance systems upstream of the power plant.

To ensure navigation at a dam site, ship locks are the most effective technique available. For small craft, lifts and elevators can be used with success. Navigation locks can also be used as fish ways with some adjustments to the equipment. Sometimes, it is necessary to increase the upstream attraction flow. In some projects, by-pass or diversion channels have been dug around the dam.

5.6.1.7 Involuntary Population Displacement

Although not all hydropower projects require resettlement, involuntary displacement is part of the most sensitive socio-economic issues surrounding hydropower development. It consists of two closely related, yet distinct processes: displacing and resettling people as well as restoring their livelihoods through the rebuilding or “rehabilitation” of their communities.

When involuntary displacement cannot be avoided, the following measures might contribute to optimise resettlement outcomes:

- involving affected people in defining resettlement objectives, in identifying reestablishment solutions and in implementing them; rebuilding communities and moving people in groups, while taking special care of indigenous peoples and other vulnerable social groups;
- publicizing and disseminating project objectives and related information through community outreach programs, to ensure widespread acceptance and success of the resettlement process;
- improving livelihoods by fostering the adoption of appropriate regulatory frameworks, by building required institutional capacities, by providing necessary income restoration and compensation programs and by ensuring the development and implementation of long-term integrated community development programs;
- allocating resources and sharing benefits, based upon accurate cost assessments and commensurate financing, with resettlement timetables tied to civil works construction and effective executing organizations that respond to local development needs, opportunities and constraints.

5.6.1.8 Affected People and Vulnerable Groups

Like in all other large-scale interventions it is important during the planning of hydropower projects to identify through a proper social impact study who will benefit from the project and especially who will be exposed to negative impacts. Project affected people are individuals living in the region that is impacted by a hydropower project’s preparation, implementation and/or operation. These may be within the catchment, reservoir area, downstream, or in the periphery where project-associated activities occur, and also can include those living outside of the project affected area who are economically affected by the project. Particular attention needs to be paid to groups that might be considered vulnerable with respect to the degree to which they are marginalized or impoverished and their capacity and means to cope with change. Although it is very difficult to mitigate or fully compensate the social impacts of large hydropower projects on indigenous or other culturally vulnerable communities for whom major transformations to their physical environment run contrary to their fundamental beliefs, special attention has to be paid to those groups in order to ensure that their needs are integrated into project design and adequate measures are taken. Negative impacts can be minimised for such communities, if they are willing partners in the development of a hydropower project, rather than perceiving it as a development imposed on them by an outside agency with conflicting values. Such communities require to be given sufficient lead time, appropriate resources and communication tools to assimilate or think through the project's consequences and to define on a consensual basis the conditions in which they would be prepared to proceed with the proposed development. Granting a long-term financial support for activities which define local cultural specificities may also be a way to minimize impacts as well as ensuring early involvement of concerned communities in project planning; to reach agreements on proposed developments and economic spin-offs between concerned communities and proponents. Furthermore, granting legal protections so that affected communities retain exclusive rights to the remainder of their traditional lands and to new lands obtained as compensation might be an appropriate mitigation measure as well as to restrict access of non-residents to the territory during the construction period while securing compensation funds for the development of community infrastructure and services such as access to domestic water supply or to restore river crossings and access roads. Also, it is possible to train community members for project-related job opportunities.

5.6.1.9 Public Health

In warmer climate zones the creation of still standing water body such as reservoirs can lead to increases in waterborne diseases like malaria, river blindness, dengue or yellow fever, although the need to retain rainwater for supply security is most pressing in these regions. In other zones, a temporary increase of mercury may have to be managed in the reservoir, due to the liberation of often airborne mercury from the soil through bacteria, which can then be entering in the food chain in form of methyl mercury. Moreover, higher incidences of behavioural diseases linked to increased population densities are frequent consequences of large construction sites. Therefore public health impacts should be considered and addressed from the outset of the project. Reservoirs that are likely to become the host of waterborne disease vectors require provisions for covering the cost of health care services to improve health conditions in affected communities. In order to manage health effects related to a substantial population growth around hydropower reservoirs, it may be considered to control the influx of migrant workers or migrant settlers as well as to plan the announcement of the project in order to avoid early population migration to an area not prepared to receive them. Moreover, mechanical and/or chemical treatment of shallow reservoir areas could be considered to reduce proliferation of insects carrying diseases, while planning and implementing disease prevention programs. Also, it may be considered to increase access to good quality medical services in project-affected communities and in areas where population densities are likely to increase as well as to put in place detection and epidemiological monitoring programs, to establish public health education programs directed at the populations affected by the project as well as to implement a health plan for work force and along the transportation corridor to reduce risk for transmittable diseases (e.g. STD).

5.6.1.10 Cultural heritage

Cultural heritage is the present manifestation of the human past and refers to sites, structures and remains of archeological, historical, religious, cultural and aesthetic value (World Bank 1994 a). Exceptional natural landscapes or physical features of our environment are also an important part of human heritage as landscapes are endowed with a variety of meanings. The creation of a reservoir might lead to disappearance of valued exceptional landscapes such as spectacular waterfalls and canyons. Long-term landscape modifications can also be incurred by soil erosion, sedimentation, low water levels in reservoirs as well as through associated infrastructure impacts (e.g. new roads, transmission lines). It is therefore important that appropriate measures are taken to preserve natural beauty in the project area and to protect cultural properties with high historic value.

Possible measures to minimise negative impacts are for example to ensure on site protection, conservation and restoration or relocation and/or re-creation of important physical and cultural resources, to create a museum in partnership with local communities to make archaeological findings, documentation and record keeping accessible, to include landscape architecture competences into the project design to optimise harmonious integration of the infrastructure into the landscape, to use borrow pits and quarries for construction material which will later disappear through impoundment, to re-vegetate dumping sites for soil and excavation material with indigenous species, to put transmission lines and power stations underground in areas of exceptional natural beauty, incorporate residual flows to preserve important waterfalls at least during the touristic high season, to keep as much as possible the natural appearance of river landscapes by constructing weirs using local rocks to adjust the water level instead of concrete weirs, and by constructing small islands in impounded areas.

5.6.1.11 Sharing of Development Benefits

There is no doubt that well sited and designed hydropower projects have a substantial potential to generate significant national and regional economic benefits. It is difficult to overstate the economic importance of hydropower and irrigation dams for densely populated countries that are affected by scarce water resources for agriculture and industry, limited access to indigenous sources of oil, gas or coal, and frequent shortages of electricity. In many cases, however, hydropower projects have resulted both in winners and losers: affected local communities have often born the brunt of project-related economic and social losses, while the regions to which they are connected have benefited from better access to affordable power and to regulated downstream water flows and water levels. Although economic benefits are often substantial, effective enhancement measures should ensure that local and regional communities fully benefit from the hydropower project. This may take many forms including business partnerships, royalties, development funds, equity sharing, job creation and training, jointly managed environmental mitigation and enhancement funds, improvements of roads and other infrastructures, recreational and commercial facilities (e.g. tourism, fisheries), sharing of revenues, payment of local taxes, or granting preferential electricity rates and fees for other water-related services to local companies and project-affected populations.

5.6.2 Guidelines and regulations

The assessment and management of the above impacts represent a key challenge for hydropower development. The issues at stake are very complex and have often been subject of intense controversy (Goldsmith *et al.*, 1984). Moreover, unsolved socio-political issues, which are often not project related, tend to come up to the forefront of the decision-making process in a large-scale infrastructure development (Beauchamp, 1997).

All in all, the planning of larger hydropower developments can be rather complex due to the wide range of stakeholders[6] involved in the preparation, funding, construction and operation of a hydropower project, as those stakeholder need to acquire a common and clear understanding of the associated environmental and social impacts, risks and opportunities. Therefore guidelines and regulations are needed to ensure that those impacts are assessed as objectively as possible and managed in an appropriate manner. In many countries a strong national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated through a licensing process and follow-up obligations enshrined into the operating permit often also known as concession agreement. Yet, discrepancies between various national regulations as well as controversies have lead to the need to establish international guidelines on how to avoid, minimise, compensate negative impacts while maximising the positive ones.

Besides the international financing agencies' safeguard policies, one of the first initiatives was launched in 1996 by countries like Canada, USA, Norway, Sweden and Spain for which hydropower is an important energy resource. Their governments set up in collaboration with their mainly state-owned hydropower utilities and research institutions a five-year research program under the auspices of the International Energy Agency (IEA, 2000b) called "Hydropower and the Environment". This IEA research program relied on the assessment of more than 130 hydropower projects, involving more than 110 experts from 16 countries, the World Bank and the World Commission on Dams (WCD). The WCD was established in 1998 to review the development effectiveness of large dams, to assess alternatives for water and power development, and to develop acceptable criteria, guidelines and standards, where appropriate, for the planning, design, appraisal, construction, operation, monitoring and decommissioning of dams. It has set on five core values[7], seven strategic priorities[8] and twenty-six guidelines (WCD, 2000). While governments, financiers and the industry have widely endorsed the WCD core values and strategic priorities, they consider the guidelines to be only partly applicable. As a consequence, international financial institutions such as World Bank (WB), Asian Development Bank (ADB), African Development Bank (AfDB) or the European Bank for Reconstruction and Development (EBRD) have not endorsed the WCD report as a whole, in particular not its guidelines, but they have kept or developed their own guidelines and criteria (WB, 2001). All major export credit agencies (ECAs) have done the same (Ecologic, 2008). Whereas the WCD's work focused on analysing the reasons for shortcomings with respect to poorly performing dams, its follow-up initiative the "Dams and Development Project" (DDP) hosted by UNEP, put an emphasis on gathering good practice into a compendium (UNEP, 2007). In a similar perspective, the IEA launched in 2000 a second hydropower specific 5-year research program called "Hydropower Good Practice" (IEA, 2006).

Even though the International Finance Corporation's Performance Standards and the Equator Principles have become the most widely-accepted general framework among international project financiers for managing environmental and social risks and opportunities of projects in the developing world, the need remains for a specific practical reference tool to properly assess the economic, social and environmental performance of hydropower projects. In order to meet this need, the International Hydropower Association (IHA) has produced Sustainability Guidelines (IHA, 2004) and a Hydropower Sustainability Assessment Protocol (IHA, 2006) which are based on the broadly shared five core values and seven strategic priorities of the WCD report, while it has taken the hydropower-specific previous IEA study as starting point (IEA, 2000b). In 2007, a detailed analysis of the tools available for the environmental criteria for hydropower development

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[6] E.g. local population, governments, developers, financing institutions, NGOs and others

[7] Equity, efficiency, participatory decision-making, sustainability, and accountability

[8] Gaining public acceptance, comprehensive options assessment, addressing existing dams, sustaining rivers and livelihoods, recognising entitlements and sharing benefits, ensuring compliance, sharing rivers for peace, development and security

was conducted on behalf of the ADB, Mekong River Commission, and the Worldwide Fund for Nature. The report concludes that "*the IHA Sustainability Guidelines appears to be the most comprehensive and a possible best starting point for the Greater Mekong Sub region*" (ADB-MRC-WWF, 2007). This industry initiated process remains open to continued improvement and has recently (March 2008) be broadened to a systematic integration of other parties concerns through the Hydropower Sustainability Assessment Forum. This multi-stakeholder working group is financed by the governments of Germany, Iceland and Norway as well as by the World Bank and is carrying out further expert review of the IHA Hydropower Sustainability Assessment Protocol and the process of its application.

5.6.3 Life-cycle assessment and GHG emissions of hydropower

Life cycle assessment (LCA) allows taking into account a macro-perspective by comparing impacts of all available technology options in a comprehensive cradle to grave approach. This paragraph only focuses on the climate change indicator (IPCC – 100 years), e.g. greenhouse gas emissions (GHG). LCA of electricity generation in terms of GHG emissions was elaborated by the International Energy Agency (IEA, 2000b). In contrast with thermal generating units, in the case of hydro, there is no GHG emissions associated with the fuel production and fuel transportation, but only with the electricity generation itself. LCA of a hydroelectric kWh consists of 3 main stages:

- **Construction:** in this phase, GHG are from the production and transportation of construction materials (e.g. concrete, steel, etc) and the use of civil work equipments (diesel engines). Those data can differ significantly from one project to another and are rarely available.
- **Operation and maintenance**: when a hydro reservoir is created the carbon cycle can be modified and in some cases net GHG emissions may occur (see below). Additional GHG emissions can be generated by operation and maintenance activities (building heating/cooling system, auxiliary diesel generating units, staff transportation, etc).
- **Dismantling:** dams can be decommissioned for economic, safety or environmental reasons. Up to now, only few small-size dams have been removed, mainly in the USA. During this phase GHG emissions are emitted due to transportation/storage/recycling of materials, diesel engines, etc.

LCAs carried out on hydropower projects up to now have clearly demonstrated the difficulty to establish generalities regarding this particular technology, among others because most of the projects are multi-purpose projects. Yet, a study carried out by IEA (2000b) based on LCA and later published in Energy Policy (EIA, 2002), the amount of CO_2 – equivalent emitted by hydropower is around 15g CO2eq/kWh. Similarly, a study carried out in 2002 by IEA and CRIEPI on the Japanese system has shown LCA GHG emissions to be around 11g CO2eq/kwh. These emissions from mainly temperate and Nordic reservoirs rank very low compared to those of thermal power plants, which would typically be in the range of 500-1000 g CO_2eq /kWh. However, significantly different results can be obtained in some cases under particular circumstances, which are covered in more details hereafter.

Research and field surveys on freshwater systems involving 14 universities and numerous experts from all over the world (Tremblay *et al.*, 2005) have lead to the following conclusions:

- All freshwater systems, whether they are natural or man made, emit greenhouse gases (GHG) due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHG.

- Within a given region that shares similar ecological conditions, reservoirs and natural water systems produce similar levels of emissions per unit area. In some cases, natural water bodies and freshwater reservoirs even absorb more GHG than they emit.

Reservoirs are collection points of material coming from the whole drainage basin area upstream. As part of the natural cycle, organic matter is flushed into these collection points from the surrounding terrestrial ecosystems. In addition, domestic sewage, industrial waste and agricultural pollution will also enter these systems and produce GHG emissions, the cause of which should not be attributed to the collection point. Therefore it is a challenge to estimate man-made GHG emissions from flooded lands, as they must consider only the net emissions by subtracting the natural emissions from the wetlands, rivers and lakes that were located in the area before impoundment and abstract carbon inflow from the riparian terrestrial ecosystems as well as other human activities.

The main GHG produced in freshwater systems are carbon dioxide (CO_2,) and methane (CH_4). The nitrous oxide (N_2O) could be also an issue in some cases and more particularly in tropical areas or in reservoirs with large drawdown zones. Yet with respect to N_2O emissions, no global estimation exists presently. Studied reservoirs in boreal environment would emit a low quantity of N_2O, while a recent study does not allow determining clearly whether tropical reservoirs are neutral or sources of N_2O for the atmosphere (Guerin et al. 2008b).

For most of the studied reservoirs, two GHG pathways from the reservoir to the atmosphere have been studied (Figure 5.23): ebullition and diffusive fluxes from the surface of the reservoir. CH_4 transferred through diffusive fluxes from the bottom to the water surface of the reservoir may undergo oxidation, that is to say transformed in CO_2, in the water column nearby the oxicline[9] when methanotrophic bacteria are present. In addition, studies at Petit-Saut, Samuel and Balbina have investigated GHG emissions downstream of the dam (degassing just downstream of the dam and diffusive fluxes along the river course downstream of the dam). Regarding N_2O, Guérin et al. (2008b) have identified several possible pathways for N_2O emissions: emissions could occur via diffusive flux, degassing and possibly through macrophytes but this last pathway has never been quantified neither in boreal or tropical environment.

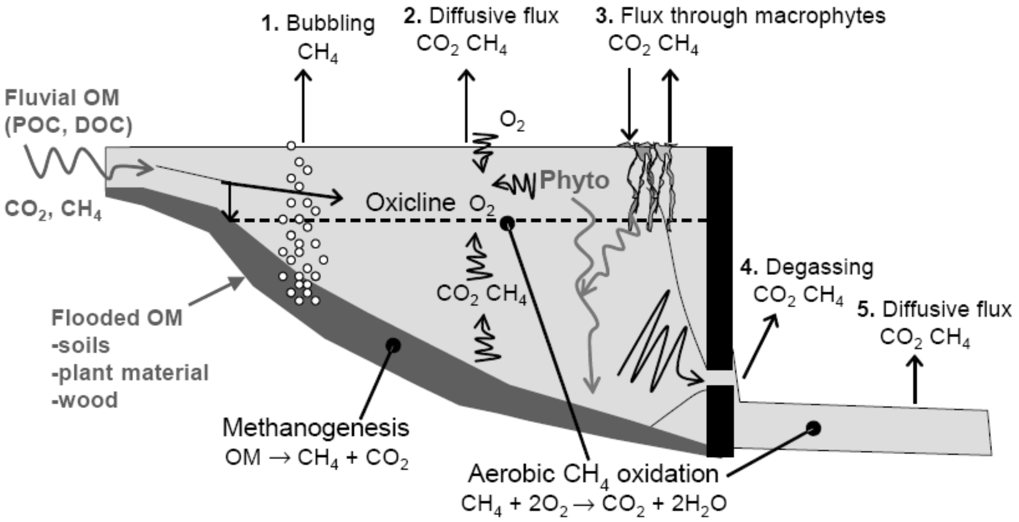

Figure 5.23: Evolution of the E&S process, adopted from UNEP (2007).

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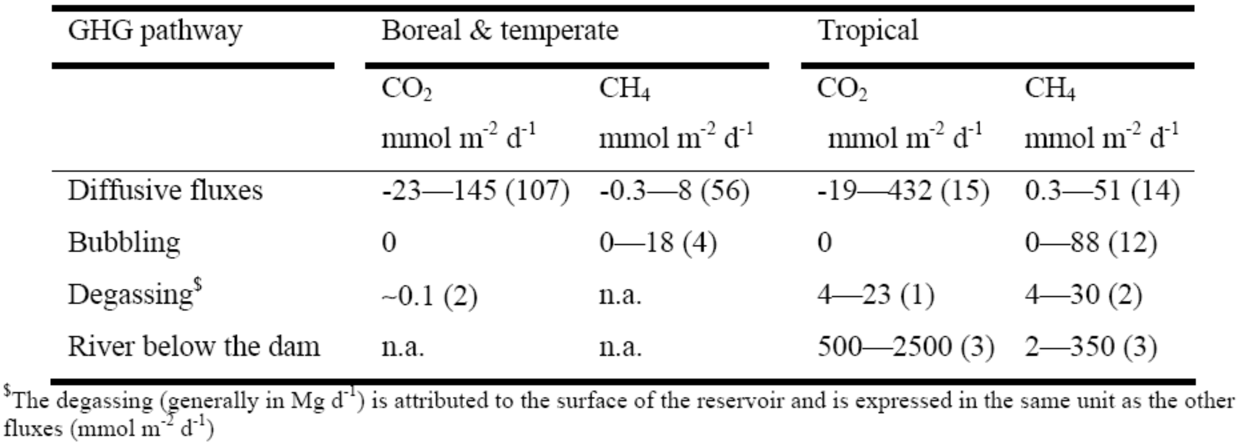
[9] Lisstrom et al. 1984; Frenzel et al. 1990; Guerin et al. 2007

Carbon dioxide and methane pathways in freshwater reservoir with an anoxic hypolimnion ((IJHD, 2005); Guerin et al. 2007; Guerin et al 2008b).

Still, for the time being, only a limited amount of studies appraising the net emissions from freshwater reservoirs (i.e. excluding unrelated anthropogenic sources and pre-existing natural emissions) is available, whereas gross emissions have been investigated in boreal[10] and temperate[11] regions. Gross emissions measurements in boreal/temperate regions from Canada, Finland, Iceland, Norway, Sweden and USA are summarized in Table 5.5. below.

Table 5.5: Range of gross CO2 and CH4 emissions from hydroelectric freshwater reservoirs. Numbers in parentheses are the number of studied reservoirs (UNESCO-RED, 2008).



GHG pathway	Boreal & temperate		Tropical	
	CO_2 mmol m^{-2} d^{-1}	CH_4 mmol m^{-2} d^{-1}	CO_2 mmol m^{-2} d^{-1}	CH_4 mmol m^{-2} d^{-1}
Diffusive fluxes	-23—145 (107)	-0.3—8 (56)	-19—432 (15)	0.3—51 (14)
Bubbling	0	0—18 (4)	0	0—88 (12)
Degassing$	~0.1 (2)	n.a.	4—23 (1)	4—30 (2)
River below the dam	n.a.	n.a.	500—2500 (3)	2—350 (3)

$The degassing (generally in Mg d^{-1}) is attributed to the surface of the reservoir and is expressed in the same unit as the other fluxes (mmol m^{-2} d^{-1})

In tropical regions, high temperatures coupled with important demand in oxygen due to the degradation of substantial OM amounts favour the production of CO_2, the establishment of anoxic conditions and thus the production of CH_4. OM is mainly coming from submerged biomass, usually very dense, and soil organic carbon (Abril et al. 2005; Guerin et al. 2008). According to UNESCO/IHA (2008) measurements of gross emissions have been taken in the tropics at four Amazonian locations[12] and additional sites in central and southern Brazil[13] . Measurements are not available from reservoirs in other regions of the tropics or subtropics except for Gatum in Panama, Petit-Saut in French Guyana and Nam Theun 2, Nam Ngum and Nam Leuk in Lao PDR. Preliminary studies on Nam Ngum and Nam Leuk indicate that an old reservoir might act as a carbon sink under certain conditions[14]. This underlines the necessity to also monitor old reservoirs. The age of the reservoir has proved to be an important issue as well as the organic carbon standing stock, water residence time, type of vegetation, season, temperature, oxygen and local primary production, themselves dependent on the geographic area (Fearnside 2002). According to IPCC (2006), evidence suggests that CO_2 emissions for approximately the first ten years after flooding are the results of decay of some of the organic matter on the land prior to flooding, but, beyond this time period, these emissions are sustained by the input of inorganic and organic carbon material transferred into the flooded area from the watershed. In boreal and temperate conditions, GHG

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[10] Rudd 1993; Duchemin et al., 1995; Kelly et al. 1997; Huttunen et al. 2002; Tremblay et al. 2005

[11] Therrien et al. 2005; Soumis et al. 2004; Casper et al. 2000) and tropical (Keller and Stallard 1994; Rosa and Scheaffer 1994; Galy-Lacaux et al. 1997; Galy-Lacaux et al. 1999; Fearnside 1995; Fearnside 1997; Fearnside 2001; Fearnside 2002; Delmas et al. 2001; Rosa et al. 2003; Abril et al. 2005; Sikar et al. 2005; Santos et al. 2006; Guerin et al. 2008; Kemenes et al. 2007

[12] Balbina, Curuá-Una, Samuel, Tucuruí

[13] Barra Bonita, Carvalho, Corumbá, Funil, Furnas, Itaipu, Itumbira, L.C.B., Manso, Mascarenhas de Moraes, Miranda, Ribeirão das Lajes, Serra da Mesa, Segredo, Três Marias, Xing (Duchemin et al. 1995

[14] data scheduled to be published during the first semester of 2010

emissions have been observed to return to the levels found in neighbouring natural lakes after the initials years following impoundment (Tremblay *et al.*, 2005). Further measurements could resolve this question for tropical conditions. Comparisons of these results are not easy to achieve, and require intense data interpretation, as different methodologies (equipment, procedures, intensity, units of measurement, etc.) were applied for each study. Few measurements of material transported into or out of the reservoir have been reported, and few studies have measured carbon accumulation in reservoir sediments (UNESCO/IHA 2008)[15].

More coordinated research is needed to establish a robust methodology to accurately estimate the change in GHG emissions caused by the creation of a reservoir: the net GHG emissions. Since 2008, UNESCO and IHA have been hosting an international research project, which aims to improve through a consensus-based, scientific approach, the understanding of reservoir induced impacts, excluding unrelated anthropogenic sources as well as natural GHG emissions from the watershed. The goals are to gain a better understanding on the processes involved and to overcome knowledge gaps.

5.6.4 Multiplier effects of hydropower projects

Dam projects generate numerous impacts both on the region where they are located, as well as at an inter-regional, national and even global level (socio-economic, health, institutional, environmental, ecological, and cultural impacts). The WCD and numerous other studies have discussed the importance and difficulties of evaluating a number of these impacts. One of the issues raised by these studies is the need to extend consideration to indirect benefits and costs of dam projects (Bhatia, Scatasta and Cestti, 2003). According to the WCD's Final Report (2000) "*a simple accounting for the direct benefits provided by large dams - the provision of irrigation water, electricity, municipal and industrial water supply, and flood control - often fails to capture the full set of social benefits associated with these services. It also misses a set of ancillary benefits and indirect economic (or multiplier) benefits of dam projects*". Indirect impacts are called multiplier impacts, and are resulting from both inter-industry linkage impacts (increase in the demand for an increase in outputs of other sectors) and consumption-induced impacts (increase in incomes and wages generated by the direct outputs). Multipliers are summary measures expressed as a ratio of the total effects (direct and indirect) of a project to its direct effects. A multi-country study on multiplier effects of large hydropower projects was performed by the World Bank (2005), which estimates that the multiplier values for large hydro projects are varying from 1.4 to 2.0, what means that for every dollar of value generated by the sectors directly involved in dam related activities, another 40 to 100 cents could be generated indirectly in the region.

5.7 Prospects for technology improvement and innovation,

Hydropower is a mature technology where most components have been tested and optimised during long term operation. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency. Older turbines can have lower efficiency by design or reduced efficiency due to wear from sediments. It is therefore a potential to increase energy output by retrofitting new equipment with improved efficiency and usually also with increased capacity. Most of the existing hydropower equipment in operation today will need to be modernized during the next three decades, opening up for improved efficiency and higher power and energy output (UNWWAP, 2006).

The structural elements of a hydropower project, which tend to take up about 70 percent of the initial investment cost, have a projected life of about 100 years. On the equipment side, some refurbishment can be an attractive option after thirty years. Advances in hydro technology can

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[15] More information can be found at http://www.hydropower.org/climate_initiatives.html.

justify the replacement of key components or even complete generating sets. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the life of the project, making more effective use of the same flow of water (UNWWAP, 2006).

DOE reported that a 6.3 percent generation increase could be achieved in the USA from efficiency improvements if plant units fabricated in 1970 or prior years, having a total capacity of 30,965 MW, are replaced. Based on work done for the Tennessee Valley Authority (TVA) and other hydroelectric plant operators, a generation improvement of 2 to 5.2 percent has also been estimated for conventional hydropower in the USA (75,000 MW) from installing new equipment and technology, and optimizing water use (Hall *et al.*, 2003). In Norway it has been estimated that increase in energy output from existing hydropower from 5-10% is possible with a combination of improved efficiency in new equipment, increased capacity, reduced head loss and reduced water losses and improved operation.

There is much ongoing research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are described briefly in the following section. Most of the new technologies under development aim at utilizing low (< 15m) or very low (< 5m) head, opening up many sites for hydropower that have not been possible to use by conventional technology. Most of the data available on hydropower potential is based on field work produced several decades ago, when low head hydro was not a high priority. Thus, existing data on low head hydro potential may not be complete. As an example, in Canada a potential of 5000 MW has recently been identified for low head hydro alone (Natural Resources Canada, 2009).

Another example, in Norway the economical and environmentally feasible small hydropower potential (<10 MW) was previously assumed to be 7 TWh. A new study initiated in 2002-2004, revealed a small hydropower potential of nearly 25 TWh at a cost below 0.06 US$/KWh and 32 TWh at a cost below 0.09 US$/KWh (Jensen, 2009).

5.7.1 Variable speed technology

Usually, hydro turbines are optimized for an operating point defined by speed, head and discharge. At fixed speed operation, any head or discharge deviation involves an important decrease in efficiency. The application of variable speed generation in hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values. In addition to improved efficiency, the abrasion from silt in the water will also be reduced. Substantial increases in production with respect a fixed-speed plant have been found in simulation studies (Terens *et al.*, 1993) (Fraile-Ardanuy, 2006).

5.7.2 Matrix technology

A number of small identical units comprising turbine-generator can be inserted in a frame the shape of a matrix where the number of (small) units is adapted to the available flow. During operation, it is possible to start and stop any number of units so those in operation can always run under optimal flow conditions. This technology is well suited to install at existing structures for example irrigation dams, low head weirs, ship locks etc where water is released at low heads (Schneeberger *et al.*, 2004).

5.7.3 Fish-friendly turbines

Fish-friendly turbine technology is an emerging technology that provides a safe approach for fish passing though hydraulic turbines minimizing the risk of injury or death. While conventional hydro turbine technologies focus solely on electrical power generation, a fish-friendly turbine brings about benefits for both power generation and protection of fish species (Natural Resources Canada, 2009).

5.7.4 Hydrokinetic turbines

Generally, projects with a head under 1.5 or 2 m are not viable with traditional technology. New technologies are being developed to take advantage of these small water elevation changes, but they generally rely on the kinetic energy in the stream flow as opposed to the potential energy due to hydraulic head. These technologies are often referred to as kinetic hydro or hydrokinetic (see Chapter 6.3 for more details on this technology). Hydrokinetic devices being developed to capture energy from tides and currents may also be deployed inland in both free-flowing rivers and in engineered waterways such as canals, conduits, cooling water discharge pipes, or tailraces of existing dams. One type of these systems relies on underwater turbines, either horizontal or vertical. Large turbine blades would be driven by the moving water, just as windmill blades are moved by the wind; these blades would turn the generators and capture the energy of the water flow (Wellinghoff *et al.*, 2007).

"Free Flow" or "hydrokinetic" generation captures energy from moving water without requiring a dam or diversion. While hydrokinetics includes generation from ocean tides, currents and waves, it is believed that it is most practical application in the near term is likely to be in rivers and streams.

In a “Policy Statement” issued on November 30, 2007 by the Federal Energy Regulatory Commission in the USA (Federal Energy Regulatory Commission, 2007) it is stated that:

“*Estimates suggest that new hydrokinetic technologies, if fully developed, could double the amount of hydropower production in the United States, bringing it from just under 10 percent to close to 20 percent of the national electric energy supply. Given the potential benefits of this new, clean power source, the Commission has taken steps to lower the regulatory barriers to its development.*”

A study from 2007 concluded that the current generating capacity of hydropower of 75 000 MW in the USA (excluding pumped storage) could be nearly doubled, including a contribution from hydrokinetic in rivers and constructed waterways of 12 800 MW (EPRI, 2007).

The potential contribution from very low head projects and hydrokinetic projects are usually not included in existing resource assessments for hydropower (See 5.2). The assessments are also usually based on rather old data and lower energy prices than today and future values. It is therefore highly probable that the hydropower potential will increase significantly as these new sources are more closely investigated and technology is improved. The examples from the USA show an increase by 20% or more for hydrokinetic projects alone, up to double the existing capacity if all types of new potential for hydropower are utilized.

5.7.5 Abrasive resistant turbines

Water in rivers will often contain large amounts of sediments, especially during flood events when soil erosion creates high sediment loads. In reservoirs the sediments may have time to settle, but in run-of-the-river projects most of the sediments may follow the water flow up to the turbines. If the sediments contain hard minerals like quarts, the abrasive erosion on guide vanes, runner and other steel parts may become very high, and quickly reduce efficiency or destroy turbines completely within a very short time (Lysne *et al.*, 2003; Gummer, 2009). Erosive wear of hydro turbine runners is a complex phenomenon, depending on different parameters such as particle size, density and hardness, concentration, velocity of water, and base material properties. The efficiency of the turbine decreases with the increase in the erosive wear. The traditional solution to the problem has been to build de-silting chambers to trap the silt and flush it out in bypass outlets, but it is very difficult to trap all particles, especially the fines. New solutions are being developed by coating steel surfaces with a very hard ceramic coating, protecting against erosive wear or delaying the process.

The problem of abrasive particles in hydropower plants is not new, but is becoming more acute with increasing hydropower development in developing countries with sediment rich rivers. For example, many new projects in India, China and South America are planned in rivers with high sediment concentrations (Gummer, 2009).

5.7.6 Tunnelling technology

Tunneling technology is used widely in hydropower to transport water from intake up to the turbines, and back to the river or reservoir downstream. Technology in use today includes both drilling and blasting (D&B) and tunneling boring machines (TBM). Recently, new equipment for very small tunnels (0.7 – 1.3 m diameter) based on oil-drilling technology, has been developed and tested in hard rock in Norway, opening up for directional drilling of “penstocks” for small hydropower directly from power station up to intakes, up to one kilometer or more from the power station (Jensen, 2009). This could lower cost and reduce the environmental and visual impacts from above-ground penstocks for small hydropower, and open up for even more sites for small hydro.

5.7.7 Dam technology

The International Commission on Large Dams (ICOLD), has recently decided to focus on better planning of existing and new (planned) hydropower dams. It is believed that over 30 billion US$ will be invested in new dams during the next decade, and the cost can be reduced by 10-20% by more cost-effective solutions. ICOLD also wants to promote multi-purpose dams and better planning tools for multi-purpose water projects (Berga, 2008). Another main issue ICOLD is focusing on is that of small dams, less than 15 meters high.

The RCC (Roller Compacted Concrete) dam is relatively new dam type, originating in Canada in the 1970s. This dam type is built using much drier concrete than in other gravity dams, and it allows a quicker and more economical dam construction (as compared to conventional concrete placing methods). It is assumed that this type of dams will be much more used in the future, lowering the construction cost and thereby also the cost of energy for hydropower projects.

5.7.8 Optimization of operation

Hydropower generation can be increased at a given plant by optimizing a number of different aspects of plant operations, including the settings of individual units, the coordination of multiple unit operations, and release patterns from multiple reservoirs. Based on the experience of federal agencies such as the Tennessee Valley Authority and on strategic planning workshops with the hydropower industry, it is clear that substantial operational improvements can be made in hydropower systems (DOE Hydropower Program Biennial Report, 2006). In the future, improved hydrological forecasts combined with optimization models is likely to improve operation and water use, increasing the energy output from existing power plants significantly.

5.8 Cost trends

5.8.1 Cost of project implementation

The total hydropower generation potential has been described in section 5.2.1. This potential is not easy to estimate exactly, since it is not only a function of natural resources (water and head) but also limited by the cost of development. The resource potential data for hydropower is in general based upon a large number site-specific studies where only those projects that were considered economically and environmentally feasible have been included.

In a recent study (Gagnon, 2009) the global unexploited hydropower resources have been estimated and grouped according to cost of development. This study is mostly based upon information from known sites provided by countries to the *Hydropower and Dams World Atlas,* 2008. Based on this information, the remaining unexploited potential for hydropower development was estimated for 18 countries/regions in the world. Data for these 18 regions have here been grouped into six larger regions or continents, similar as used previously in 5.2.1 [TSU: Reference to Table 5.6 is missing]. The remaining potential (TWh/year) for each region were divided into three classes, A, B and C, based on energy cost (¢/KWh).

- A: Economically feasible projects – energy cost between 2 and 8 ¢/KWh
- B: Realistic projects – energy cost between 8 and 20 ¢/KWh
- C: Technical potential – energy cost above 20 ¢/KWh

Class A contains projects from known sites with costs lower than or at similar levels as the main competitors today, coal, nuclear, gas etc.

Class B contains projects from known sites that are not considered economically feasible today, in competition with coal, gas and nuclear, but with a cost lower than or similar as other renewables (wind, solar etc).

Class C contains projects from main rivers or known sites that are considered technically feasible, but have a cost higher than other competing technologies. This class has not been included in the resource potential described previously (5.2.1) but it is included here to show the large potential that could be exploited at a higher cost.

The variability in cost for individual projects within each class is not known in detail, but as an approximation we suggest to use a nearly linear distribution curve within each class, ranging from 2 to 8 ¢/KWh with an average cost of 5 ¢/KWh in class A and from 8 to 20 ¢/KWh with an average of 14 ¢/KWh in Class B. For Class C no distribution can be estimated yet, since most projects here are not studied in detail due to the high cost.

Table 5.6: Unexploited Hydropower potentials by Region (TWh/year) (Source: Gagnon, 2009)

Region	**Class A 2- 8 c/kWh**	**Class B 8 – 20 c/kWh**	**Class C > 20 c/kWh**	**Total**
Africa	1023	574	2324	3921
Asia	3894	2457	1612	7963
Europe	905	168	5605	6678
North America	912	598	4607	6117
South America	1600	842	6317	8759
Australia/Oceania	70	28	7955	8053
Sum	8404	4667	28420	41491

As an example, *Hall et al.* (2003) did a study in USA, where 2155 sites with a potential capacity of 43 000 MW were examined and classified according to unit cost in $/KW. The distribution curve show that costs varied from less than 500 $/KW up to over 6000 $/KW (Figure 5.24). Except from a few projects with very high cost, the distribution curve is nearly linear, up to 95% of the projects. Lako *et al.* (2003) presented a similar trend in cost curves for several regions of the world. Gordon (1982) presented cost equation for hydropower project based on a statistical analysis of cost data obtained over 170 hydropower projects worldwide.

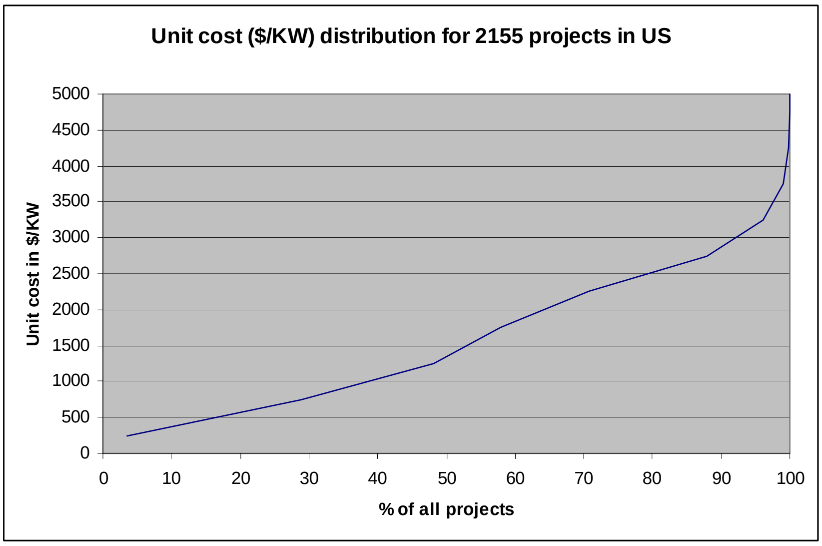

Figure 5.24: Distribution of unit cost ($/KW) for 2155 hydropower project sites studied in USA. (Source: Hall et al., 2003).

Development cost of hydropower also cost on Licensing, Plant construction, Fish and wildlife mitigation, Recreation mitigation, Historical and archeological mitigation and Water quality monitoring cost. Hall *et al*. (2003)in their study also presented typical plant construction cost for new sites in Fig 5.25.

Basically, there are two major cost groups: the civil construction costs, which normally are greater costs, and those that have to do with electromechanical equipment for energy transformation. The civil construction costs follow the price trend of the prices in the country where the project is going to be developed. In the case of countries with economies in transition, the costs are relatively low due to the use of local labor, and local materials.

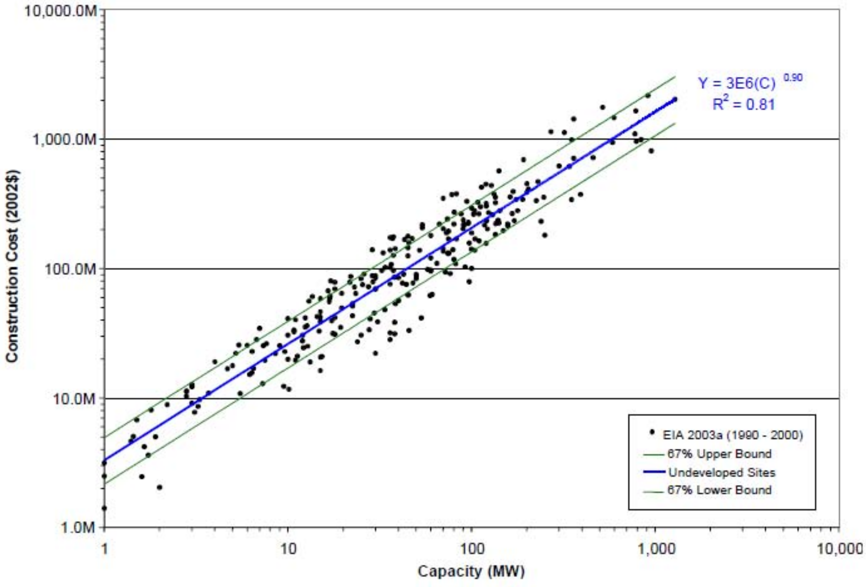

Figure 5.25: Hydropower cost as a function of plant capacity for new sites.

The costs of electromechanical projects follow the tendency of prices at a global level, except in developed countries, where most of the machinery used in the hydropower project is produced, and where prices are more stable. The issue of estimating costs and projections is not an obstacle for the development of hydroelectricity as a renewable resource. Although cost estimates are specific for each site, due to the inherent characteristics of the geological conditions and the construction design of the project, for a sound estimate of electromechanical equipment costs, it is possible to have cost estimates that follow a tendency. Avarado-Anchieta (2009,) presented the cost of electromechanical equipment from various hydroelectric projects as figure 5.26.

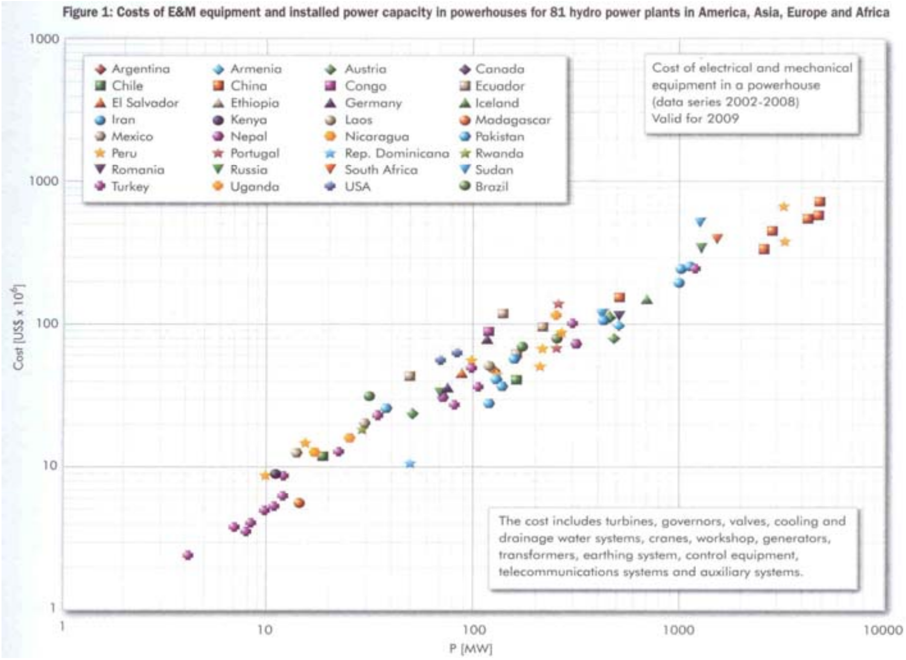

Figure 5.26: Costs of E&M equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa.

Specific installation costs (per installed MW) tend to be reduced for a higher head and installed capacity of the project. This is important in countries or regions where differences of level can be used to advantage. The hydropower project can be set up to use less volume flow, and therefore smaller hydraulic conduits or passages, also the size of the equipment is smaller and costs are lower.

Isolated systems have to be more expensive than systems that can be built near centers of consumption. There is a tendency towards lower costs if projects are in a cascade, all along a basin, given that the water resource is used several times

Use of local labor and materials also reduces cost, which is an advantage for small scale hydroelectric projects. Costs associated with the number of generator units in a hydropower project increase when the number of unit’s increases, but this is compensated by a greater availability of the hydroelectric plant into the electric grid. In hydropower projects where the installed power is lower than 5 MW, the electromechanical equipment costs are dominating. As the power to be installed increases, the costs are more influenced by the civil construction. The components of the construction project that impact the total cost, the most are the dam and the hydraulic pressure conduits; therefore these elements have to be optimized during the engineering design stage.

5.8.2 Cost allocation for other purposes

There is a greater need of sharing the cost of hydropower stations serving multipurpose like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation. Many of the purposes cannot be served alone due to consumptive nature and different priority of use. Cost allocation often has no absolute correct answer. The basic rules are that the allocated cost to any purpose does not exceed that benefit of that purpose and each purpose will carrying out at its separable cost. Separable cost for any purpose is obtained by subtacting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included (Dzurik, 2003). Three commonly used cost allocation methods are: the separable cost-remaining benefits method, the alternative justifiable expenditure method and the use-of-facilities method (Hutchens, 1999).

Until recently, reservoirs were mostly funded and owned by the public sector, thus project profitability and their inter purpose was cast sharing was not the highest considerations or priority in the decision. Nowadays, the liberalisation of the electricity market has set new economic standards in the funding and management of dam based projects. The investment decision is based on an evaluation of viability and profitability over the full life cycle of the project. The merging of economic elements (energy and water selling prices) with social benefits (supplying water to farmers in case of lack of water) and the value of the environment (to preserve a minimum environmental flow) are becoming tools for consideration for cost sharing of multipurpose reservoirs (Skoulikaris, 2008)

Votruba *et al.* (1988) reported the practice in Chechoslovakia for cost allocation in proportion to benefits and side effects expressed in monetary units. In the case of the Hirakund project in India, the principle of alternative justifiable expenditure method was followed with the allocation of the costs of storage capacities between flood control, irrigation and power was in the ratio of 38:20:42 (Jain, 2007). Government of India later adopted the use-of-facilities method for allocation of joint costs of multi-purpose river valley projects (Jain, 2007).

5.9 Hydropower future deployment

5.9.1 Overall worldwide hydro development

The figure 5.27 presents the development of hydropower :

- historical data: the use of hydropower has expanded gradually worldwide in the past years from about 1000 TWh in 1965 to more than 3000 TWh today
- forecast scenarios: the trends to 2100 is a significant increase.

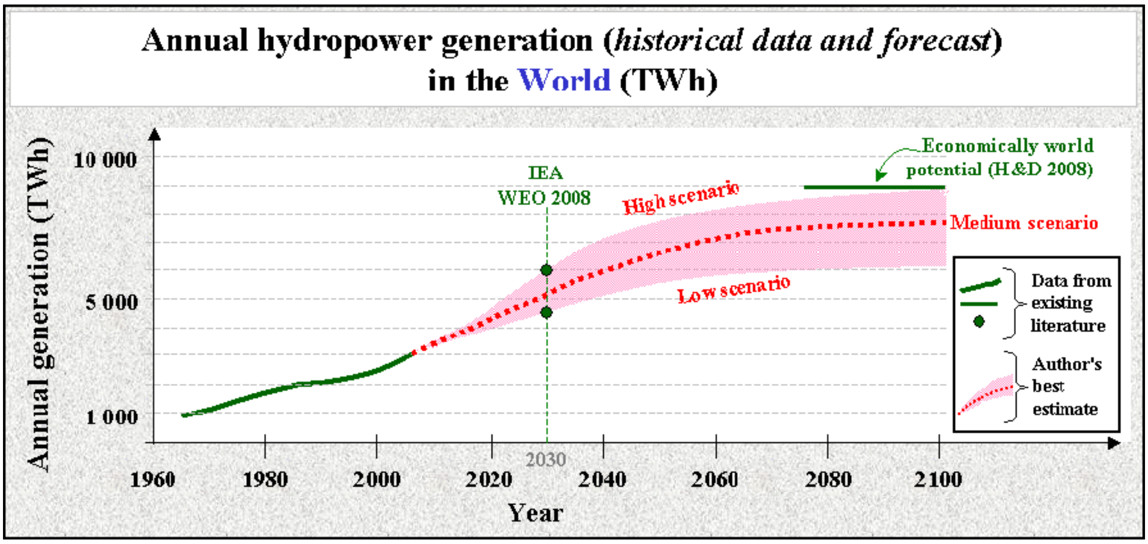

Figure 5.27: Annual Hydropower generation in the world.

At the moment, only one third of the economically feasible hydropower potential has been developed so far across the World (e.g. 3 000 TWh out of ~9 000 TWh).

The different long term prospective scenarios propose a significant increase for the next decades. For instance in 2030, the hydro generation capacity is between 4 500 TWh to more than 6 000 TWh as an annual generation (IEA, 2008).

5.9.1.1 Hydro development by regions

There are subsequent differences among regions, as it was presented below:

- **Europe and Eurasia**: European Union has developed most of its potential but there are however several possibilities to increase its hydropower capacity: rehabilitation and refurbishment of the existing units, development of small hydro, and possible new large plants to fulfil the EU RES targets. In this region the remaining potentials are mostly located in Russia and Turkey. Figure 5.28 presents development in Europe and Eurasia.

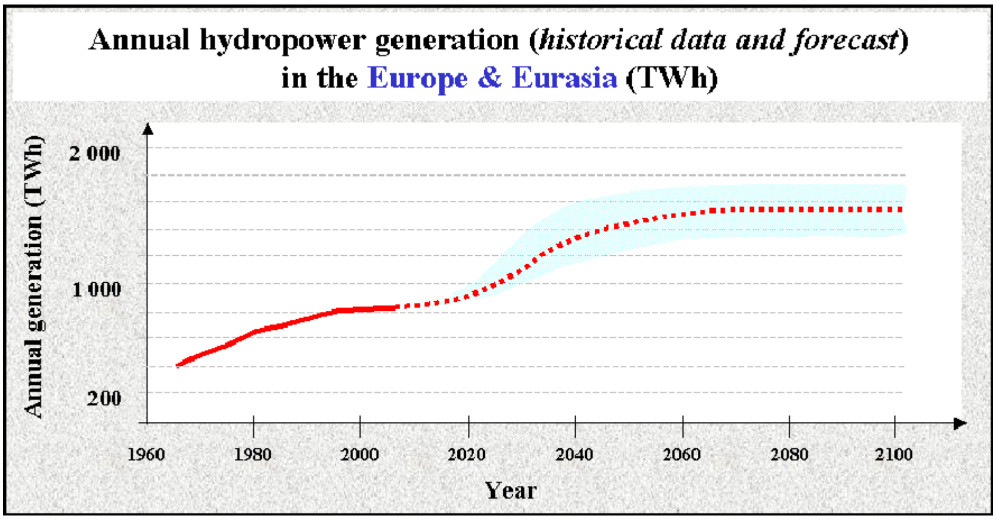

Figure 5.28: Annual Hydropower generation in Europe and Eurasia

- **North America**: even though a large amount of the potential has been so far developed, Canada (and also United States of America) is likely to continue to develop their potential considering national laws on RES, and GHG constraints. Figure 5.29 presents development in Northe America.

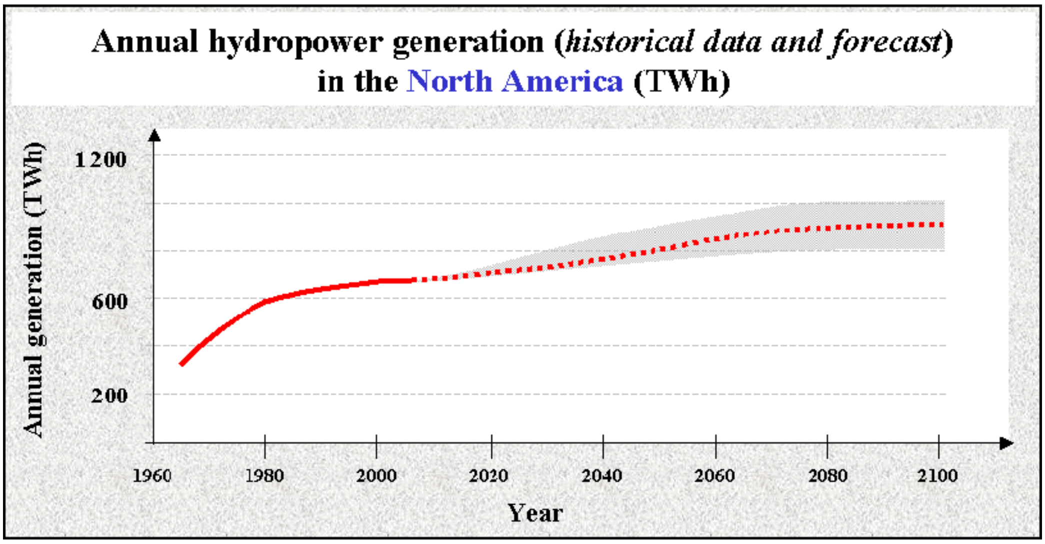

Figure 5.29: Annual Hydropower generation in North America.

- **Africa**: less than 10% of the potential has been developed. The development will rely on the main countries: Democratic Republic of Congo, Ethiopia, Cameroon, Sudan, Uganda, Zambia and Mozambique. Fig 5.30 presents development in Africa.

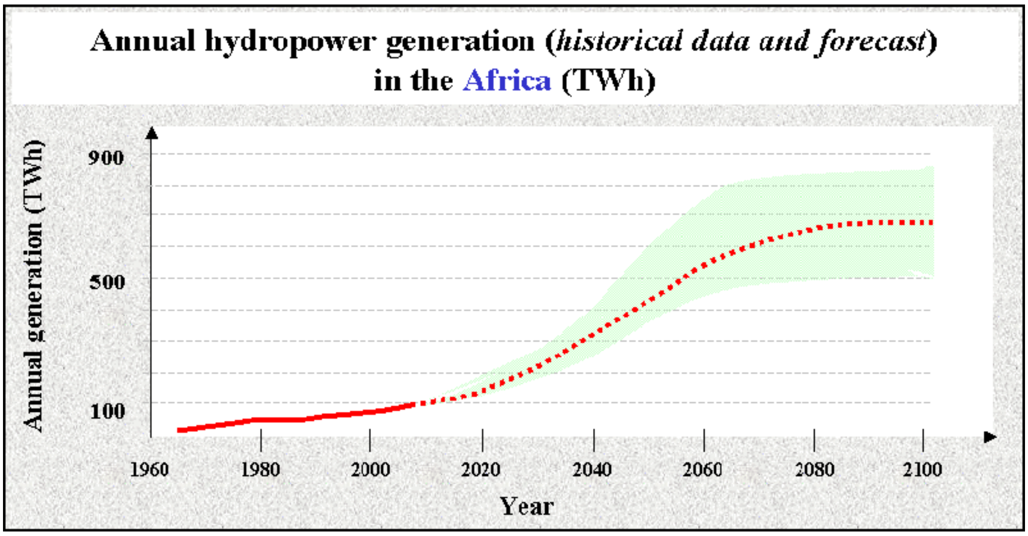

Figure 5.30: Annual Hydropower generation in Africa.

- **South and Central America**: the growth will be mainly driven by Brazil, but also several other countries such as Peru, Ecuador, Chile and Colombia will contribute to the increase. Fig 5.31 presents hydropower development in South and Central America.
- **Asia Pacific**: the growth will be mainly driven by China and India in the region. There will be also a significant increase in Mekong basin (Laos, Myanmar, etc.) and in Himalaya area (Bhutan and Nepal). Fig 5.32 presents hydropower development in Asia Pacific region.

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. These issues must be addressed in a holistic way as pieces of the same puzzle and therefore it is not practical to look at them in isolation.

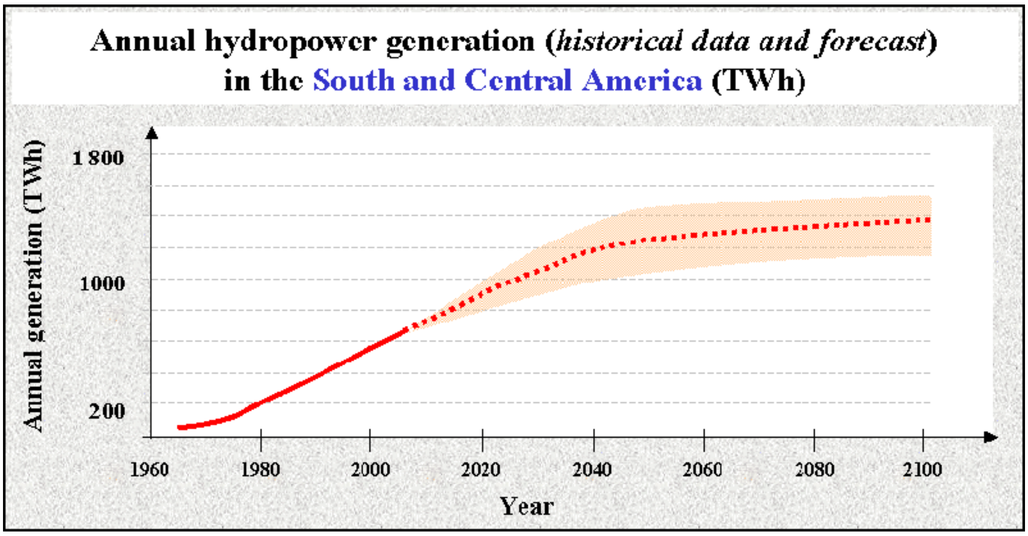

Figure 5.31: Annual Hydropower generation in South and Central America.

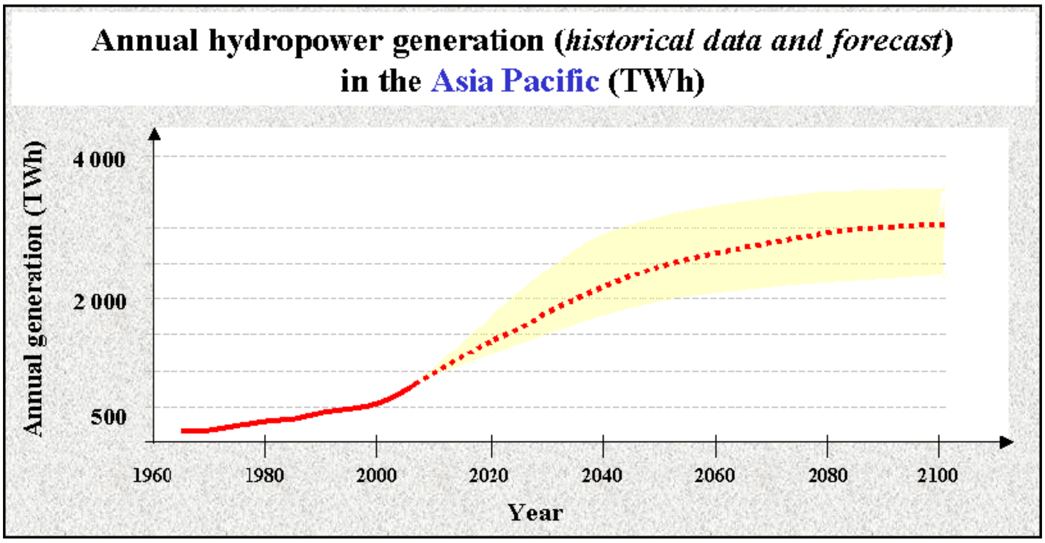

Figure 5.32: Annual Hydropower generation in Asia Pacific.

(WBCSD, 2009) Agriculture, and then food, is also a key component which cannot be considered independently of each other for sustainable development (UNESCO-RED, 2008). Providing energy and water for sustainable development requires global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these stakes and has a key role to play in providing both energy and water security.

Therefore hydropower development is part of water management systems as much as energy management systems, both of which are increasingly climate driven.

5.10.1 The need for climate-driven water management

As described in section 5.2.2, climate change will probably lead to changes in the hydrological regime in many countries, with increased variability and more frequent hydrological extremes (floods and droughts). This will introduce additional uncertainty into water resources management. For poor countries that have always faced hydrologic variability and have not yet achieved water security, climate change will make water security even more difficult and costly to achieve. Climate change may also reintroduce water security challenges in countries that for a hundred years have enjoyed water security. Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that 3 billion people will be living in conditions of severe water stress. Many countries with limited water availability depend on shared water resources, increasing the risk of conflict over these scarce resources. Therefore, adaptation in water management will become very important (Saghir, 2009)

Box 5.1: A need to increase investment in infrastructure for water storage and control

In order to increase security of supply for water and energy, both within the current climate and in a future with increasing hydrological variability, it will be necessary to increase investment in infrastructure for water storage and control. This is stated in one of the main messages in the World Bank Water Resources Sector Strategy (World-Bank, 2003).

”Message 4: Providing security against climatic variability is one of the main reasons industrial countries have invested in major hydraulic infrastructure such as dams, canals, dykes and interbasin transfer schemes. Many developing countries have as little as 1/100th as much hydraulic infrastructure as do developed countries with comparable climatic variability. While industrialized countries use most available hydroelectric potential as a source of renewable energy, most developing countries harness only a small fraction. Because most developing countries have

inadequate stocks of hydraulic infrastructure, the World Bank needs to assist countries in developing and maintaining appropriate stocks of well-performing hydraulic infrastructure and in mobilizing public and private financing, while meeting environmental and social standards".

The issue of mitigation is addressed in the IPCC WGIII AR4 (Mitigation), where the following seven sectors were discussed: energy supply, transportation and its infrastructure, residential and commercial buildings, industry, agriculture, forestry, and waste management. Since water issues were not the focus of that volume, only general interrelations with climate change mitigation were mentioned, most of them being qualitative. However, other IPCC reports, such as the TAR, also contain information on this issue.

Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate change are likely. Current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems. Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier.

The need for climate driven water management is often repositioning hydro development as a component of multipurpose water infrastructure projects.

5.10.2 Multi-purpose use of reservoirs

Creating reservoirs is often the only way to adjust the uneven distribution of water in space and time that occurs in the unmanaged environment.

"*In a world of growing demand for clean, reliable, and affordable energy, the role of hydropower and multipurpose water infrastructure, which also offers important opportunities for poverty alleviation and sustainable development, is expanding*." (World-Bank, 2009).

Reservoirs add great benefit to hydropower projects, because of the possibility to store water (and energy) during periods of water surplus, and release the water during periods of deficit, making it possible to produce energy according to the demand profile. This is necessary because of large seasonal and year-to-year variability in the inflow. Such hydrological variability is found in most regions in the world, and it is caused by climatic variability in rainfall and/or air temperature. Most reservoirs are built for supplying seasonal storage, but some also have capacity for multi-year regulation, where water from two or more wet years can be stored and released during a later sequence of dry years. The need for water storage also exists for many other types of water-use, like irrigation, water supply, navigation and for flood control. Reservoirs, therefore, have the potential to be used for more than one purpose. Such reservoirs are known as multi-purpose reservoirs.

About 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes (WCD, 2000). About 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multi-purpose reservoirs (WCD, 2000).

In addition to these primary objectives, reservoirs can serve a number of other uses like recreation and aquaculture. Harmonious and economically optimal operation of such multipurpose schemes may require trade-off between the various uses, including hydropower generation.

Since the majority of dams do not have a hydropower component, there is a significant market for increased hydropower generation in many of them. A recent study in the USA indicated some 20

GW could be installed by adding hydropower capacity to the 2500 dams that currently have none (UNWWAP, 2006). New technology for utilizing low heads (sec 5.7.1) also opens up for hydropower implementation in many smaller irrigation dams.

Box 5.2: Multipurpose projects in China

China is now constructing more than 90 000 MW of new hydro, and much of this development is designed for multi-purpose utilization of water resources (Zhu *et al.*, 2008).

For the Three Gorges Project, as an example, the primary purpose of the project is flood control, and more than 50% of the reservoir capacity is used for flood control. Hydropower generation from 22 400 MW of installed capacity is second and navigation is the third main purpose of the project. It is estimated that 15 million people and 1.5 million hectares of farmland will be protected for up to 100 years floods (Zhu *et al.*, 2008).

Box 5.3: Integration between Hydropower, Water Management and Climate Change – The Case of Brazil (Freitas, 2009; Freitas *et al.*, 2009).

Given the uncertainties of the current climatologic models when predicting future rainfall patterns in the Brazilian and our transboundary drainage basins, the recommendations made here are concentrated above all on reducing the vulnerabilities already detected with a view to expanding and sustaining the generation of hydroelectric power in Brazil.

A. Possibilities to integration and conflicts between hydroelectric energy and other users of water resources. The occurrence of extreme events, such as droughts and floods, more often and more severely will increase conflict among water users in the various drainage basins of Brazil. In terms of hydroelectric enterprises specifically, the increase in demand for water resources – in absolute terms and in their various forms – will require a more profound knowledge of the area where those enterprises are, as well as constant supervision of generating conditions, and not only in the power plant or in the reservoir areas. Hydrological balance will have to become more precise, surveys regarding environmental and economic impacts will have to be more detailed, etc.

B. Possibilities to integration and conflicts between hydroelectric energy and other land uses. Demographic growth and expansion of occupation (organized or not) of Brazilian territory tends to increase the number of individuals affected by hydroelectric enterprises, who then gain political power when making their demands. This means the process of making a project viable and putting it into practice becomes an extremely critical stage, since it now depends not only on long-term financing but also on increasingly longer negotiations, with higher transaction costs and fewer guarantees of success.

C. Multiple and integrated management of reservoirs. The increase in frequency and intensity of extreme events, such as the anomalous warming phenomena of the Pacific (El Niño) and Atlantic Oceans, require a more flexible approach to the management of reservoirs, apart from the mere optimization of hydroelectric power generation. Measures must be taken to reduce the negative impacts and increase the benefits to the basin and to the users involved. Such measures are taken both at the moment when the decision is made to build the power plant as well as when deciding how to manage its reservoir, and as a consequence many social costs may finally be imposed on the generating company by the Government, a tendency already observed internationally.

D. New institutional and regulatory arrangements for the generation of hydroelectric power. Reducing vulnerability in hydroelectric enterprises requires above all a major acceptance of those enterprises by society. It has to be accepted that the complexity of the most recent projects is far greater than that observed until the 1980s, essentially due to changes in legislation. Today numerous institutional arrangements and political connections must take place before the decision is made to invest in the building of a dam, a hydroelectric power plant or a large thermal power generation.

E. Technological and economic opportunities in the electricity generating sector. The reduction of vulnerability in the generating sector of the Brazilian power grid depends strongly on integration with other sources of energy and enterprises on several levels. In other words, an additional challenge to be considered concerns the changes that have occurred in the generation industry itself, both in the technological and economic fields. Technical-economic paradigms, such as those of large power plants, have been strongly opposed for instance, and new business opportunities have arisen in the field of establishing and operating small power stations.

Box 5.4: Structural and Non-Structural Actions in the drainage basins and in the management of hydroelectric potential related to climate change and water management (Freitas, 2009; Freitas *et al.*, 2009)

Take into consideration the uncertainties of the stream flow projection models, as well as the vulnerability of drainage basins and the energy sector (and, consequently, of the whole Brazilian power grid) to climate change risks.

Structural actions

1. Building/modification of physical infrastructure
2. Removal of sediments from reservoirs
3. Transfers of energy and water between drainage basins (regional and continental integration).

Non-structural actions

1. Adaptable management of existent water provision systems
2. Changes in operational guidelines
3. Hydrological Cycle Management, in others words, joint use of atmospheric, surface and underground water
4. Integrating operating systems for reservoirs
5. Increasing space-time coordination between supply and demand of water and energy, that is, between drainage basins, energy systems and climatic seasonality, variability and vulnerability. Emphasis should be given to the following factors:
    - Water
      Consumption and non-consumption uses
    - Energy
      Renewable and non-renewable resources
    - Efficient use of energy

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