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INTERGOVERNMENTAL PANEL ON climate change

Chapter 5

Hydropower

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Chapter 5: Hydropower

CONTENTS

EXECUTIVE SUMMARY

Hydropower is a renewable energy source where power is derived from the energy of water moving 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 per year 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 distribution and magnitude of the resource potential for hydropower could change due to a changing climate however the total amount of water in the hydrologic cycle will remain the same. 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 many 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 scale hydro can easily be implemented and integrated into local ecosystems and might be one of the best options for rural electrification through stand alone or local grids, while large urban areas and industrial scale grids need the flexibility and reliability of reservoir and pumped storage 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 or by purpose. There is no consensus on size wise categories. Classifications by size 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 continually advancing 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 which can 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 & uprating (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 multipurpose 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. In March 2010, 2062 hydropower projects where in the CDM pipeline, representing 27% of CDM applications.

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

This chapter describes hydropower technology. It starts with a brief historical overview of how the technology has evolved, the resource base and how it is affected by climate change, and gives a description of the technology and its social and environmental impacts. Also included is a summary of the present global and regional status of market and the hydropower industry, and projections for future development of technology and deployment of hydropower, both in the near (2015), medium (2030) and long term (2050). In this chapter the focus is solely on the generation of electrical energy from water. Mechanical energy generation for mills, water pumps, sawmills etc is not treated here.

5.1.1 Source of energy

The source of hydropower is water moving in the hydrological cycle. The source of hydropower therefore comes from the sun, since it is the solar radiation and absorbed solar energy that keeps the hydrological cycle active. Incoming solar radiation is absorbed at the land or sea surface, heating the surface and creating evaporation of water where water is available. A very large percentage, close to 50% of all the solar radiation input to the earth, is used to evaporate water and drive the hydrological cycle. The potential energy from tapping this cycle is therefore huge, but only a very limited amount may be practically harvested. Evaporated water moves into the atmosphere and increases the water vapour content in the air. Global, regional and local wind systems, generated and maintained by spatial and temporal variations in the solar energy input, will move the air and its vapour content over the surface of the earth, up to thousands of kilometres from the origin of evaporation. Finally, the vapour will condense and fall as precipitation, about 78% on oceans and 22% on land. This creates a net transport of water from the oceans to the land surface of the earth, and an equally large flow of water back to the oceans as river and groundwater runoff. It is the flow of water in the rivers that can be used to generate hydropower, or more precisely the potential energy of water moving from higher to lower ground on its way back to the ocean, driven by the force of gravity. Since most precipitation usually falls in mountainous areas, where also the elevation differences (called head by hydropower engineers) is largest, we usually find the largest potential for hydropower development in mountainous regions, or in rivers coming from such regions. The total surface runoff has been estimated to be 47 000 km^3, with a theoretical potential for hydropower generation of ca 41,000 TWh/year (UNDP/UNDESA/WEC, 2000; 2004).

Hydropower is both renewable and sustainable, it is not possible to deplete the resource as long as the sun keeps the hydrological cycle running. In fact, hydropower, wind power and ocean wave power (but not tidal power) are all generated by solar energy, and their distribution and magnitude are determined by the global climate and wind systems, water distribution and the topography. Using these sources is therefore equivalent to a direct harvesting of solar power.

5.1.2 History of hydropower development

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).

Hydropower was the first technology to generate electricity from a renewable source and is presently the only renewable where the largest plants produce between 80-100 TWh/year (Itaipu-Brazil and Three Gorges-China). Hydropower projects are always site-specific and thus designed according to the river system they inhabit. Its great variety in size gives the ability to meet both 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, especially when reservoirs are constructed.

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 hydropower plants involved large dams which submerged land to provide water storage. This has caused great concern for environmental impacts. Historic regional hydropower generation during 1965 to 2007 is shown in figure 5.1.

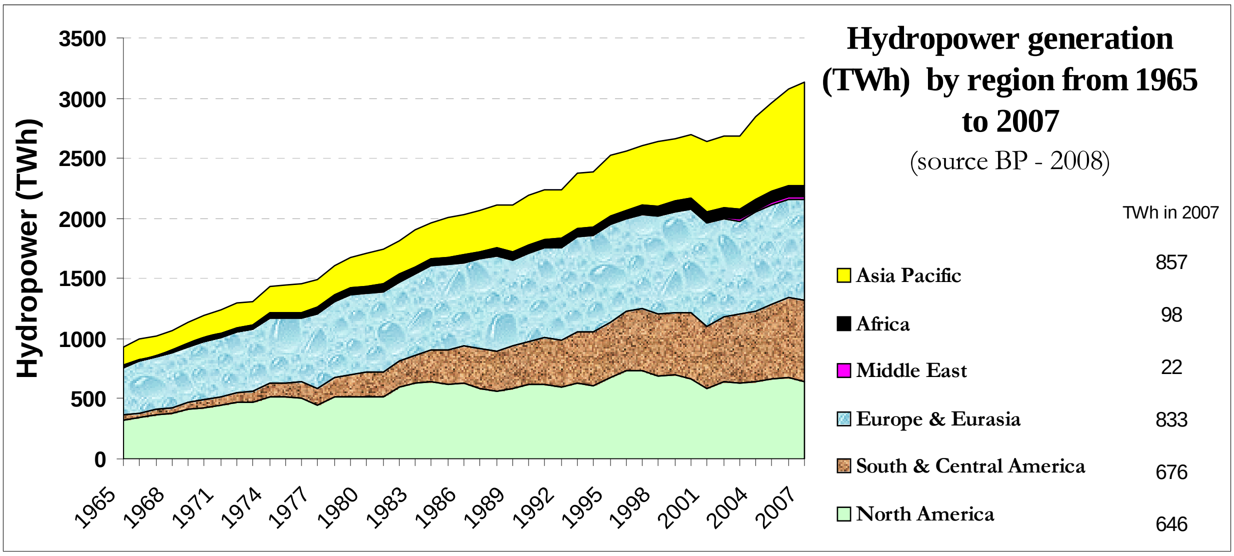

Figure 5.1: Hydropower generation (TWh) by region (BP, 2008).

5.1.3 Classification of hydropower projects

Hydropower projects can be classified by a number of ways which are not mutually exclusive:

- By size (large, medium, small, mini, micro, pico)
- By head (high or low)
- By purpose (single or multipurpose)
- By storage capacity (run-of-river, pond, seasonal, multi-year)
- By function (generation, pumping, reversible)
- By service type (base load, peaking, intermittent)
- By system design (Stand-alone or cascading)

The classification according to size (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. Small scale hydropower plants have the same components as large ones. Compared to large scale hydropower, it takes less time and efforts to construct and integrate small hydro schemes into local environments. It has therefore 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.

Impacts on ecosystems will vary, however, not so much according to installed capacity or whether or not there is a reservoir, but by the design, where intakes, dams and waterways are situated and how much water flow is used for power generation compared to how much that is left as instream flow. The concept of small versus 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. It is more fruitful to evaluate hydropower based on its sustainability performance and based on the type of service provided as opposed to a classification based on technical units with little or no relevance for nature or society.

How high the water pressure on the turbines is will be determined by the difference between the upper water level (Intake) and the outlet. This difference is called head (the vertical height of water above the turbine). Head, together with discharge, are the most important parameter for deciding the type of hydraulic turbine to be used. Generally, for high heads, Pelton turbines are used, whereas Francis turbines are used to exploit medium heads. For low heads Kaplan and bulb turbines are applied. The classification of what is “High head” and “Low head” unfortunately varies widely from country to country, and no generally accepted rules can be found.

5.1.4 Multipurpose projects

As hydropower does not consume the water that drives the turbines, the water 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 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.

5.1.5 Maturity of technology

Hydropower is a proven and well advanced technology based on more than a century of experience. Hydropower schemes are robust, highly 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. Hydropower is an extremely flexible power technology. Hydro reservoirs provide built-in energy storage, and the fast response-time of hydropower enables it to be used to optimise electricity production across power grids, meeting sudden fluctuations in demand and helping to compensate for the loss of power from other sources (IEA-ETP, 2008). Hydropower 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).

5.1.6 Policy

Hydropower infrastructure development is closely linked to more global national and regional development policies. Beyond its core role in contributing to energy security and reducing the country's dependence on fossil fuels, hydropower offers important opportunities for poverty alleviation and sustainable development. Hydropower also has a powerful contribution to make to regional cooperation, as good practice in managing water resources demands a river basin approach, regardless of national borders. In addition, multipurpose hydropower can strengthen a country's ability to adapt to climate change induced hydrological variability (World-Bank, 2009).

Hydropower development is not limited by physical or engineering potential. The main barriers are linked to a number of associated risks such as poor identification and management of environmental and social impacts, insufficient hydrological data, unexpected adverse geological conditions, lack of comprehensive river basin planning and regional collaboration, shortage of financing, scarcity of local skillful human resources. Those barriers are being addressed at policy level by a number of governments, international financing institutions (IFIs), professional associations and NGOs. Some examples of such policy initiatives impacting hydropower development are:

- The United Nations “Beijing Declaration on Hydropower and Sustainable Development“ (2004) which underscores the strategic importance of hydropower for sustainable development, calling on governments and the hydropower industry to disseminate good practice, policy frameworks and guidelines and build on it to mainstream hydropower development that is economically, socially and environmentally sustainable, in a river basin context. The Declaration also calls for tangible action to assist developing countries to finance sustainable hydropower (United-Nations, 2004).

- The Action Plan elaborated during the African Ministerial Conference on Hydropower held in Johannesburg in 2006 (ADB 2006). This Action Plan aims inter alia at strengthening the regional collaboration, fostering the preparation of feasibility studies, streamlining legal and regulatory frameworks to build human capacity, promoting synergies between hydropower and other renewables, ensuring proper benefit sharing, expanded the use of CDM for hydropower projects in Africa.

- In 2009, the World Bank Group (WBG) has released its “Directions in Hydropower” which outline the rationale for the hydropower sector expansion and describes the WBG portfolio and renewed policy framework for tackling the challenges and risks associated with scaling up hydropower development. WBG's lending to hydropower has increased from less than US$ 250 million per year from 2002-04 to over US$ 1 billion in 2008 (World-Bank, 2009). [TSU: state US$2005 instead of US$; depending on origin consider converting this figure]

- In March 2010, the International Hydropower Association (IHA) has produced a policy statement on “Hydropower and the Clean Development Mechanism”, supporting the current CDM reform being implemented by the CDM Executive Board as decided upon in Copenhagen (2009). Hydropower is the CDM's leading deployed renewable energy and CDM remains a key mechanism for fostering the mobilisation of private sector capital worldwide (Saili et al., 2010).

- The inter-governmental agreements signed between Laos and its neighbouring countries (Thailand, Vietnam, Cambodia) which create the necessary institutional framework for the development of major trans-boundary projects such as the 1088 MW Nam Theun 2 project developed under a Public-Private Partnership model (Viravong, 2008). The support of the World Bank and other IFIs has greatly helped mobilizing private loans and equity. The sales of electricity to Thailand have started in March 2010. Over the 25-year concession period, the revenues for the Government of Laos will amount to US$ 2 billion [TSU: state US$2005 instead of US$; depending on origin consider converting this figure], which will be used to serve the countries development objectives through a Poverty Reduction Fund (Fozzard, 2005).

- In India, following the announcement of a 50,000 MW hydro initiative by the Prime Minister in 2003, the Central Government has taken a number of legislative and policy initiatives, including preparation of a shelf of well-investigated projects and streamlining of statutory clearances and approval, establishment of independent regulatory commissions, provision for long-term financing, increased flexibility in sale of power, etc. India is also cooperating with Bhutan and Nepal for the development of their hydropower potential (Ramanathan et al., 2007).
- The U.S. Energy Secretary Chu said in November 2009 that hydropower capacity in the USA could “double with minimal impact to the environment”, largely by making better use of existing infrastructure. In March 2010, the U.S. Department of Energy, the U.S. Department of the Interior, and the U.S. Army Corps of Engineers signed a memorandum of understanding designed to foster development of hydropower resources that will serve the country's energy, environmental, and economic goals.

5.2 Resource potential

5.2.1 Worldwide Hydropower Potential

The International Journal of Hydropower & Dams *2005 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 which vary with time and by location.

The total worldwide generation potential is 14,368 TWh/yr (IJHD, 2005) with a corresponding estimated total capacity potential of 3,845 GW[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.

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”. However, economically feasible

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[1] Derived value based on regional generation potentials **IJHD**, 2005: World Atlas & Industry Guide. International Journal of Hydropower and Dams, Wallington, Surrey, 383 pp. and average capacity factors shown in Figure 5.3.

potentials are subject to time dependent economic conditions and the sustainability policy choices given societies make. Most notably Asia and Latin America have outstandingly large potentials and along with Australasia/Oceania they have very large potential hydropower growth factors (potential capacity as a percentage of existing capacity are 440 to 640%). 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 19 times the amount of hydropower currently installed.

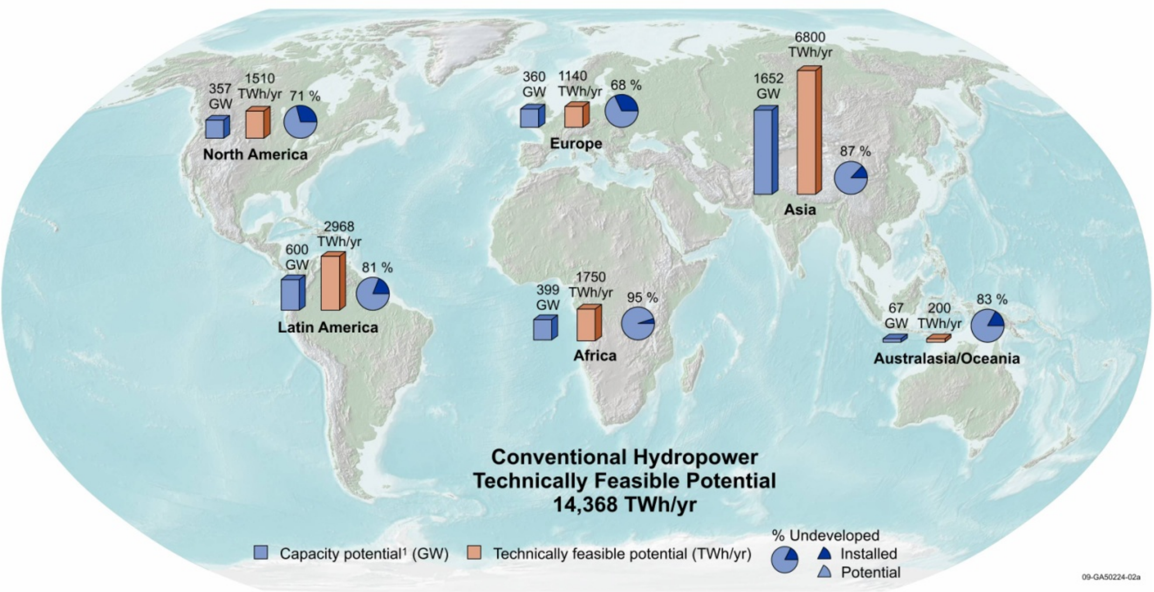


Figure 5.2: Regional hydropower potential in annual generation and capacity potential with comparisons of installed and potential capacities including undeveloped percentage of the total capacity (Source: (IJHD, 2005).

An understanding and appreciation of hydropower potential is best obtained by considering current total regional installed capacity (IJHD, 2005) and annual generation (2005/2006) (IJHD, 2007) shown in Figure 5.3. The 2005 reported worldwide total installed hydropower capacity is 746 GW producing a total annual generation of 3,032 TWh/yr averaged over 2005 and 2006. Figure 5.3 also includes regional average capacity factors calculated using regional total installed capacity and annual generation [capacity factor = generation/(capacity x 8760hrs)].

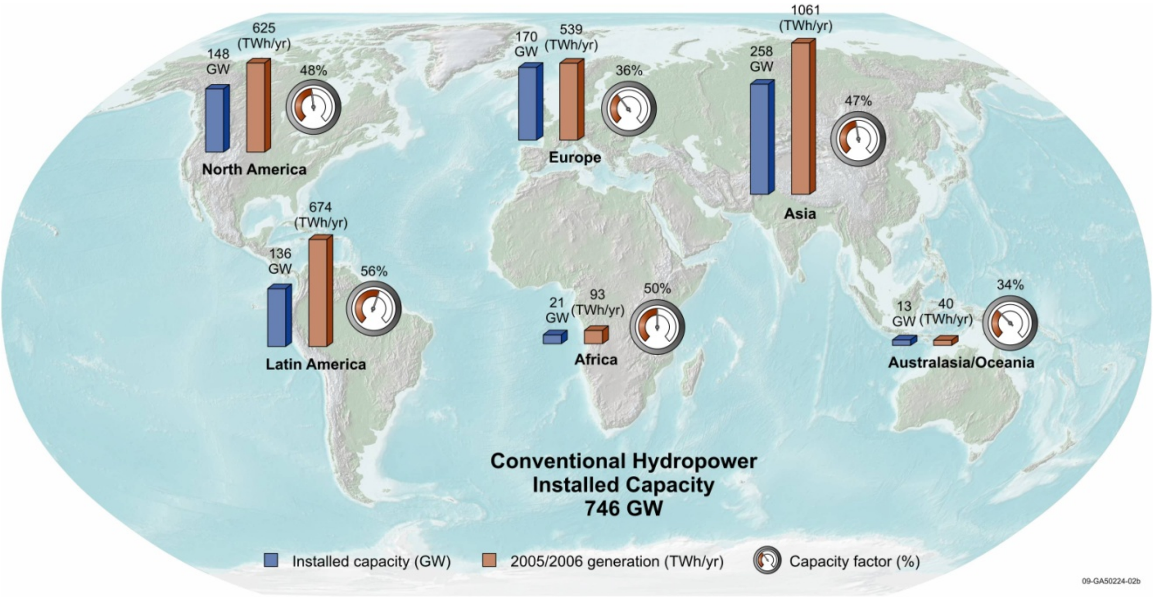


Figure 5.3: Total regional installed capacity (Source: (IJHD, 2005) 2005/2006 annual generation Source: IJHD (2007), and average capacity factor (derived as stated).

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. The average capacity factors are in the typical range for hydropower (≈ 35 to 55%). Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking vs base-load generation), water availability, or 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. While the generation potential of in-stream and constructed waterway resources have not been assessed, they are undoubtedly significant sources of emissions-free energy production based on their large extent.

Worldwide, hydropower has sufficient undeveloped potential to significantly increase its role as a full 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:

- 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;
- Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects:
- 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, and decreasing storage services.

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, 2007a) which also included discussions on impact on water resources. Later, a Technical paper on Water was prepared based on the work in WGII and other sources (Bates *et al.*, 2008). The information presented in Chapter 5.2.2 is mostly based on these two sources, with a few additions from papers and reports published in 2008 and 2009 in order to assure that it is as up to date as possible.

5.2.3 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, 2007a; 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. The figure shows % change in precipitation during 100 years, from 1990-99 to 2090-99. 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).

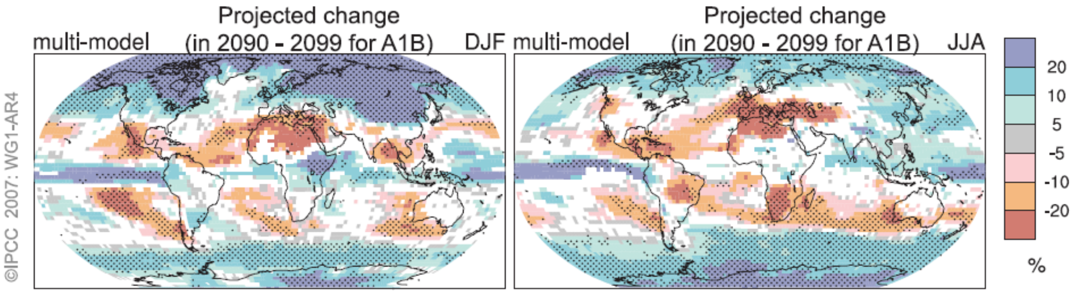


Figure 5.4: Projected multi-model mean changes in global precipitation for the SRES A1B Emission scenario. December to February at left, June to August at right. Changes are plotted only where more than 66% of the models agree on the sign of the change. The stippling indicates areas where more than 90% of the models agree on the sign of the change (IPCC, 2007b).

5.2.4 Projected changes in river flow

Changes in river flow due to climate change will primarily depend on changes in volume and timing of precipitation, evaporation and snowmelt. 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. Before data can be used in the catchment hydrological models, it is necessary to downscale data, a process where output from the GCM is converted to corresponding climatic data in the catchments. Such downscaling can be both temporal and spatial, and it is currently a high priority research area to find the best methods for downscaling.

A few global-scale studies have used runoff simulated directly by climate models (IPCC, 2007b).and hydrological models run off-line. [IPCC, 2007c] 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). Multi model ensembles approach is, however, not a guarantee of reducing uncertainty in mathematical models.

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).

5.2.5 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 IPCC (2007a). A summary from these findings are given below for each continent, with reference to IPCC (2007a) and relevant chapters:

5.2.5.1 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 (IPCC, 2007a).

5.2.5.2 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.

5.2.5.3 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 (IPCC, 2007a).

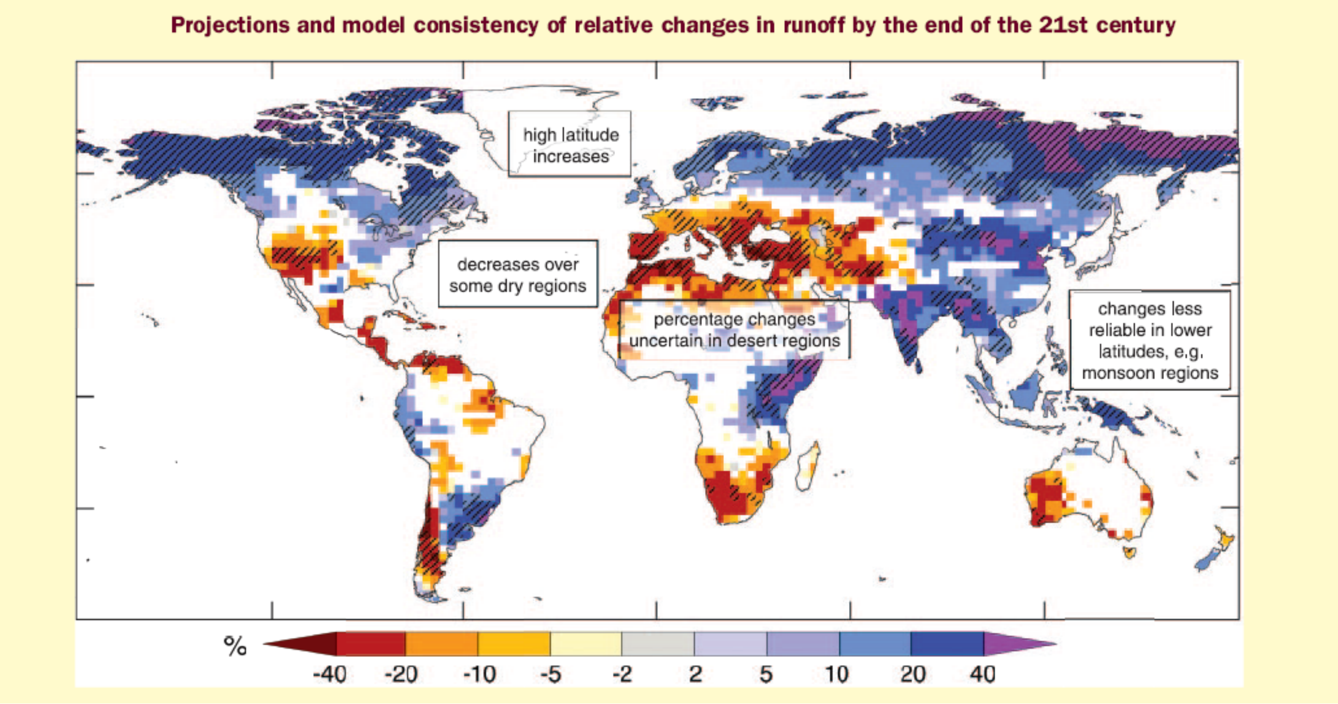


Figure 5.5: Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and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

5.2.5.4 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. Hydropower is very important in New Zealand, supplying over 60% of electricity production. In New Zealand, increased westerly wind speed is very likely to enhance wind generation and spill over precipitation into major South Island hydro-catchments, and to increase winter rain in the Waikato catchment. Warming is virtually certain to increase melting of snow, the ratio of rainfall to snowfall, and to increase river flows in winter and early spring. This is very likely to increase hydro-electric during the winter peak demand period, and to reduce demand for storage (IPCC, 2007a).

5.2.5.5 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 (IPCC, 2007a)

5.2.5.6 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 (IPCC, 2007a).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). [TSU: convert to US $ 2005] 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. [IPCC, 2007c]

5.2.5.7 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 was used (USA, Canada, Brazil, India, China and Australia). The changes in hydropower generation for the existing hydropower system (IJHD, 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. (Due to use of different sources the data in the table for 2005 will deviate slightly from those given in 5.2.1)

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 Generation 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

The somewhat surprising result from this study is that only 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 and slightly positive, when averaged over continents or globally. In practice, there might be problems to transmit surplus hydropower from regions with increasing to regions with decreasing hydropower production.

5.3 Technology and applications

5.3.1 Types

Hydro-Power Plant (HPP) is 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. Power production therefore follows the hydrological cycle in the watershed Nevertheless, some RoR HPPs also have small storage and are known as pondage-type plants.. 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 RoR HPP 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. RoR HPPs 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 HPP situated in small rivers or streams the characteristics of a variable or intermittent source. Installation of small RoR HPPs 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. RoR project may be constructed in the form of cascades along a river valley, often with a reservoir type HPP in the upper reaches of the valley that allows both to benefit from the cumulative capacity of the various power stations.

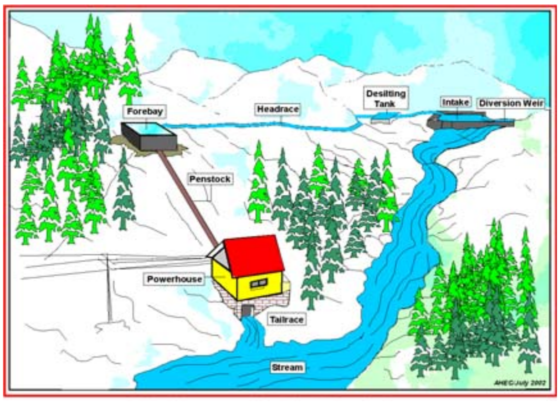


Figure 5.6: Run of river hydropower plant.

(Shivasamudram, heritage, India)

(Source: Arun Kumar, AHEC IITR, India)

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 topography.

Figure 5.7: Hydropower plants with reservoir. (1,528 MW) Manic-5, Québec, Canada
(Source: Arun Kumar, AHEC IITR, India) (Vinogg *et al.*, 2003)

5.3.1.3 *Pumped-storage*

Pumped storage hydroelectricity is a type of hydroelectric power generation used by some power plants for load balancing. Pumped-storage plants pump water from a lower reservoir 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. 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. It is considered to be one of the most efficient technologies available for energy storage. Figure 5.8 shows such type of development.

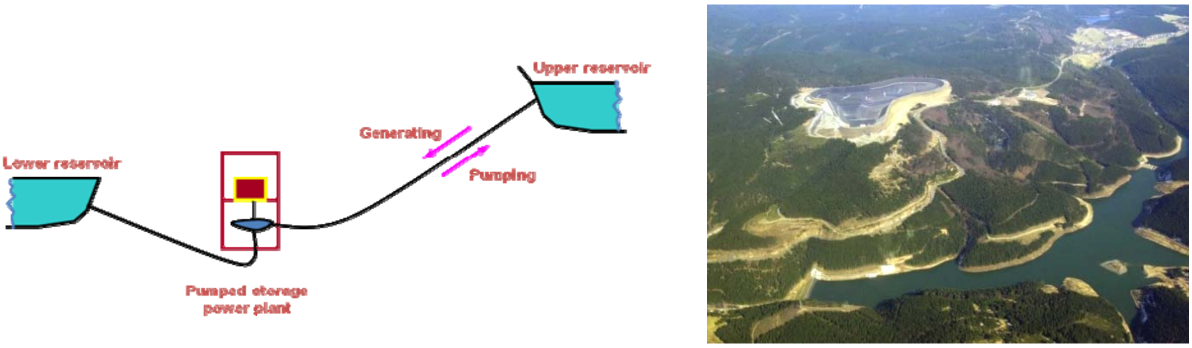


Figure 5.8: Pumped storage project (Source: IEA, 2000b). (Goldisthal, Thüringen Germany)
Source: (Taylor, 2008)

5.3.1.4 Instream technology using existing facilities

To optimise existing facilities like weirs, barrages, canals or falls, small turbines or hydrokinetic turbines can be installed for electricity generation. These are basically functioning like a run-of-river scheme shown in Figure 5.9. 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 (se 5.7.4)

Figure 5.9: Typical arrangement of instream technology hydropower projects. (Narangawal,, India)

(Source: Arun Kumar, AEHC, IITR, India)

[TSU: rephrase figure captions in 5.3.1, figures 5.7 and 5.9 not readable]

5.3.2 Status and current trends in technology development

5.3.2.1 Efficiency

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

- The amount of water available, Q_T (Million m^3 of water pr year = Mm^3/year)
- Water loss due to flood spill, bypass requirements or leakage, Q_L (Mm^3/year)
- The difference in head between upstream intake and downstream outlet, H_{gr} (m)
- Hydraulic losses in water transport due to friction and velocity change, H_L (m)
- 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, η is the efficiency of the generating unit, 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 or shall not be withdrawn. 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. The inefficiency is due to hydraulic loss in the water circuit (intake, turbine, tail-race), mechanical loss in the turbo-generator group and electrical loss 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.

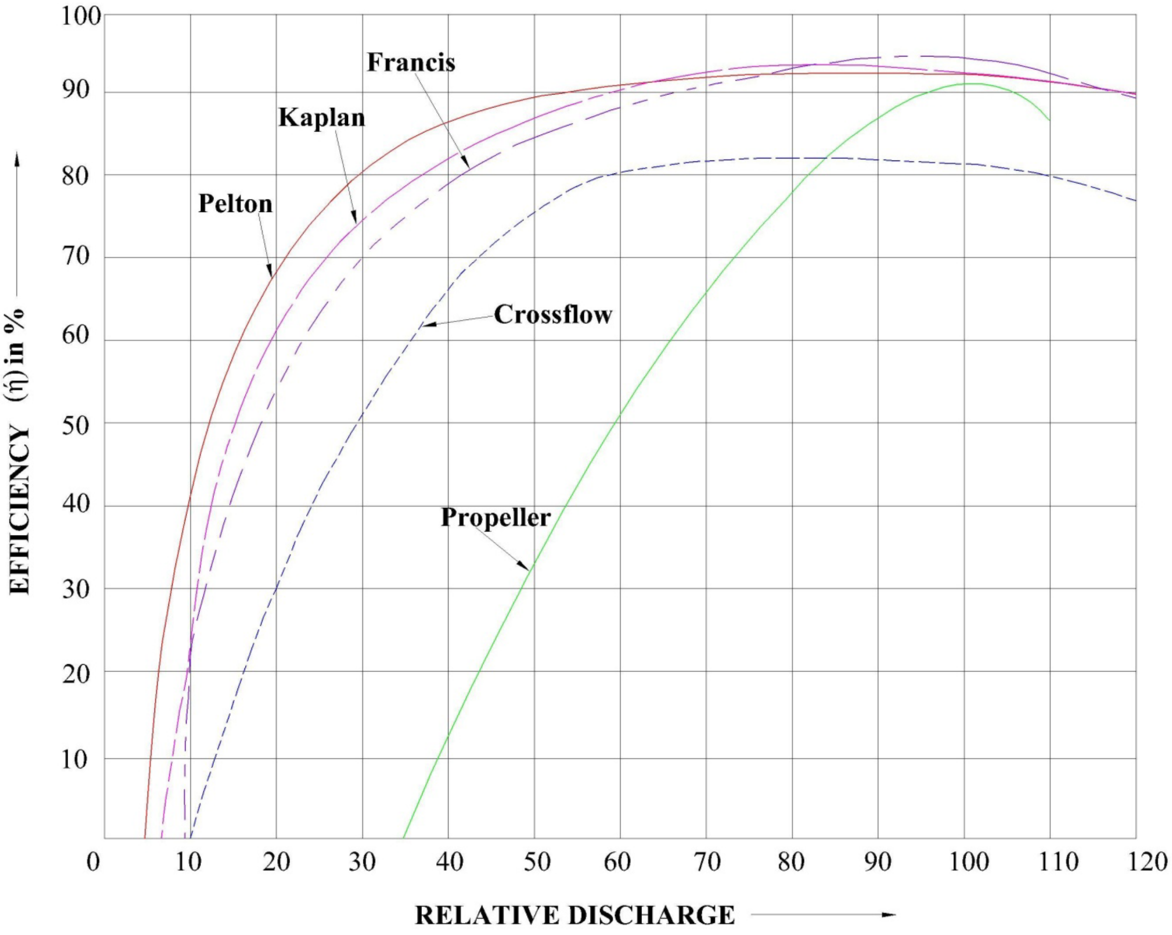


Figure 5.10: Typical efficiency curves for different types of hydropower turbines (Source: (Vinogg et al., 2003)

5.3.2.2 Tunneling capacity

5.3.2.2.1 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 where the power station is placed underground, for example for access, power cables, surge shafts and ventilation.

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

5.3.2.2.2 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") sets a predetermined pattern of holes to a selected depth in the rock face. Explosives in the holes are then detonated and loosened debris or muck 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. Thanks to the development in tunnelling technology, the excavation costs have been drastically reduced in recent 30 years (see Fig. 5.11).

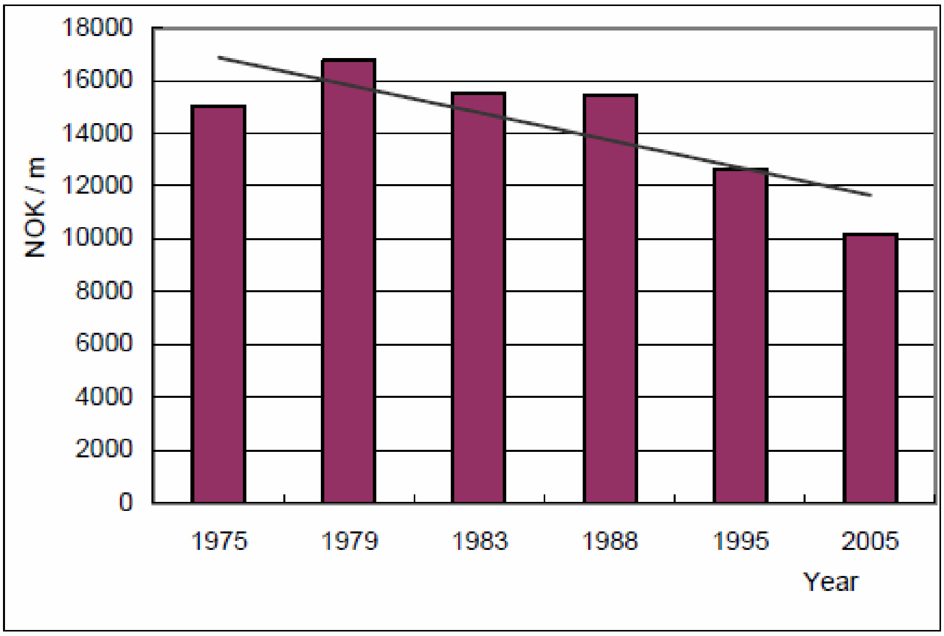


Figure 5.11: Development in tunneling technology - trend of excavation costs for a 60 m2 tunnel, price level 2005, Norwegian Kroner (NOK) pr m. (Zare et al., 2007). [TSU: convert to US $ 2005, specify technology]

5.3.2.2.3 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.

5.3.2.2.4 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 add 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 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.

For hydropower there are two kinds of projects: regulation projects with storage reservoir and run-of river, where flushing procedures using bottom gates during floods can be integrated into operation flood management to maintain stable and sustainable siltation rate in the reservoirs.

In every country, 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. For hydropower projects this 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 and analyzed. Additionally, it is necessary to establish reservoir depth (bathymetric) monitoring programmes at all storage reservoirs for hydroelectric generation, which can be easily done by taking measurements at a time pace consistent with sedimentological process (siltation, erosion) time scale. To the previous results must be correlated with studies of basin or sub-basin erosion. Several models are available for these studies.

The Revised Universal Soil Loss Equation (*RUSLE*) is a method that is widely utilized to estimate soil erosion from a particular portion of land(Renard *et al.*, 1997). In general the GIS based model (Geographical Information System) includes calibration and the use of 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 ((McCully, 2001)). Reservoirs can be significantly affected by the changes in sediment transport processes.

Reservoir sedimentation problems, due to 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 increase in volume 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).

Sedimentation can also increase downstream degradation and give increased flood risk upstream of the reservoirs, perturbing morpho dynamics and ecological functionalities. Deposition of sediments can obstruct intakes blocking the flow of water through the system and also impact the turbines. The sediment-induced wear of the hydraulic machineries is more serious when there is no 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 intakes and mechanical removal of sediment from reservoirs and for settling basins 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, mechanical removal of sediment from reservoirs, design and operate hydraulic machineries aiming to resist effect of sediment passes through them.

However, measures are not easy to apply 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 alternative strategies, choices have to be made based on 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 remains and need to be done to address sedimentation problems in hydropower projects.

It is important to note that erosion and sediment control efforts are not exclusive to hydroelectric projects, but are also an important part of national sustainability 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 & upgrading (RM&U) of old power stations is often cost effective, environment friendly and requires less time for implementation. Capacity additions through RM&U of old power stations can be attractive. 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.. The Norwegian Research Council has recently initiated a program for renewable energy where one of the projects is looking for so called win-win opportunities where the aim is to increase power production in existing power plants and at the same time improve environmental conditions (CEDREN, 2009).

Normally the life of hydro-electric power plant is 40 to 80 years. Electro-mechanical equipment may need to be upgraded or replaced after 30-40 years, while civil structures like dams, tunnels, etc usually function longer before it requires renovation. The lifespan of properly maintained hydropower plants can exceed 100 years. 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 746,000 MW of hydro equipment in operation in 2005 will need to be modernised by 2030 (SER, 2007). Refurbished or up rated existing hydropower plants also result in incremental hydropower generation due to availability of higher efficient turbines and generators also uprated and renovation of capacity. Existing infrastructure (like existing barrages, weirs, dams, canal fall structures, water supply schemes) are also being reworked by adding new hydropower facilities.

There are 45,000 large dams in the world where the majority (75%) were not built for hydropower purposes (WCD, 2000) but for the purpose of irrigation, flood control, navigation and urban water supply schemes. Retrofitting these with turbines may represent a substantial potential. Only about 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multipurpose reservoirs 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 temporally 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 the 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, and was mainly a result of increased production in China and Latin America, which grew by 399.5 TWh and 562.2 TWh, respectively (Figure 5.12).

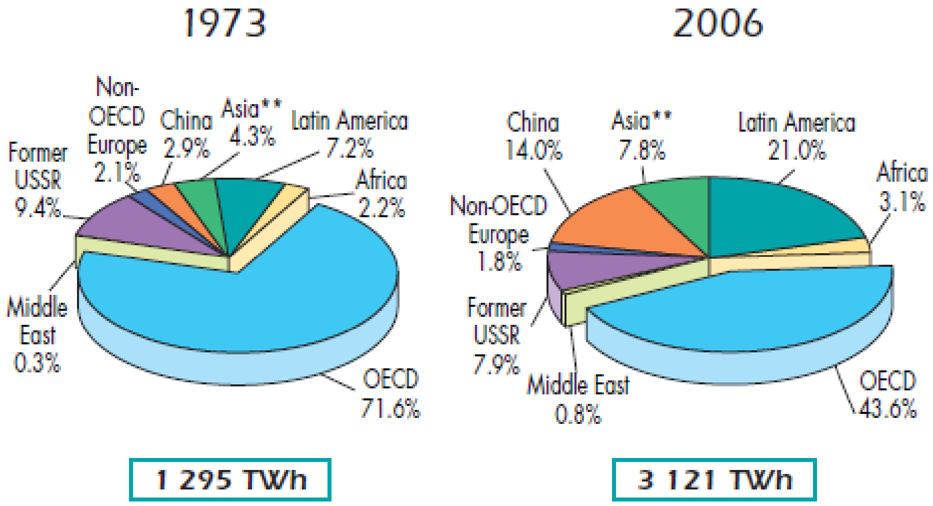


Figure 5.12: 1973 and 2006 regional shares of hydro production* (Source: IEA, 2008) [TSU: */** unspecified]

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 in China15.2%.

Table 5.2: Major Countries Producers / Installed Capacity. [TSU: caption not clear]

Country	**Installed Capacity** GW (2005 data)
China	118
United States	99
Brazil	71
Canada	72
Japan	47
Russia	46
India	32
Norway	28
France	25

Country Based on Top 10 Producers	**% of Hydro in Total Domestic Electricity Generation (2006 data)**
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

Italy	21
Rest of the world	308
World	**867**

United States	7.4
Rest of the world**	14.3
World	**16.4**

**Excludes countries with no hydro production

Sources: (IEA, 2006; 2008)

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) (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. [TSU: rephrase sentence, not including Russia in DCs] In these countries capitalism, although it developed later, seems to have followed in the footsteps of the industrialized countries drawing on previously untapped sources to provide clean and safe energy, in sufficient quantities to guarantee the expansion of a solid industrial base (Freitas, 2003). Russia is however an exception given it developed hydropower and industrialized much earlier than Brazil, China and India; albeit under a non-capitalistic economic system. It faces the twin challenges of developing new hydropower projects and the challenges of maintaining an ageing hydropower infrastructure.

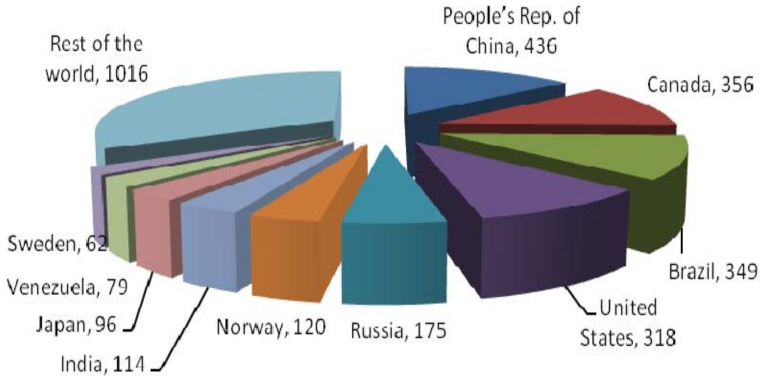
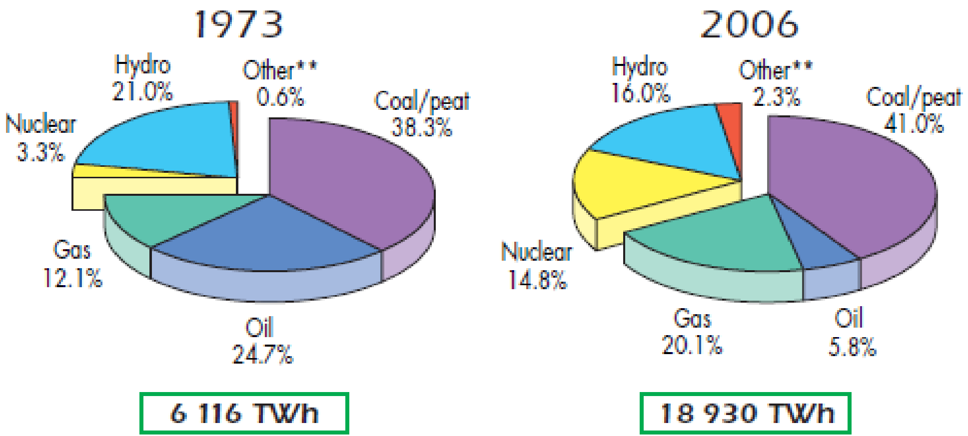


Figure 5.13: Hydro Generation by Country (TWh) (Source: IEA, 2008). [TSU: reference year missing in caption]

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%.



*Excludes pumped storage.
**Other includes geothermal, solar, wind, combustible renewables & waste, and heat.

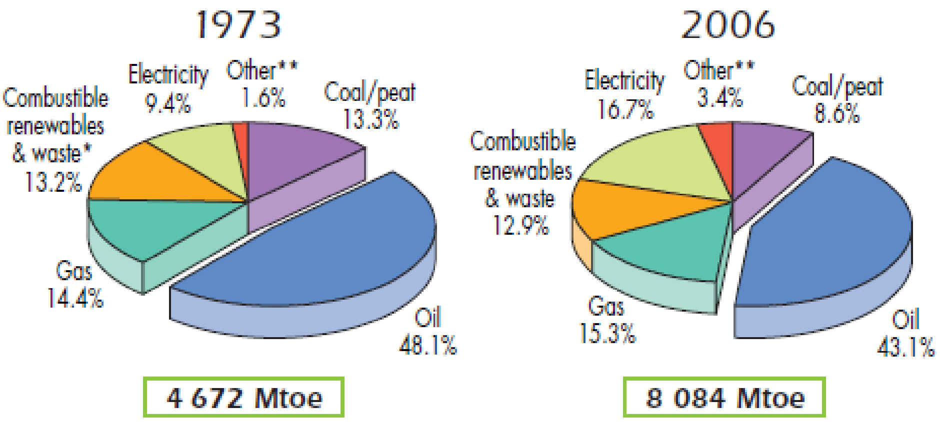
Figure 5.14: 1973 and 2006 fuel share of electricity generation* (Source: IEA, 2008).

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.

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).

Although oil accounts for the major share of final consumption electricity is the second largest energy source in 2006 (figure 5.15), in part due to the increase of electricity generation and consumption in China, 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 in terms of tons of oil equivalent toe (Source: IEA, 2008). [TSU: convert to EJ or TWh]

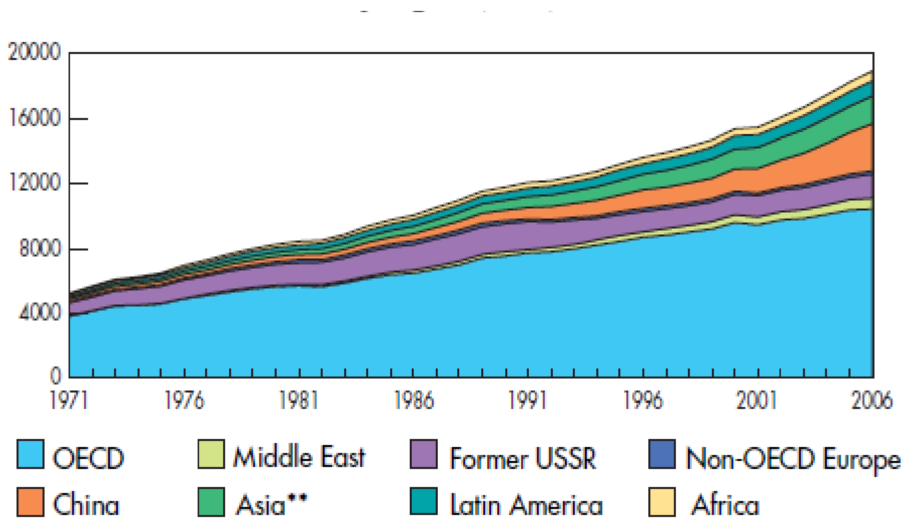


Figure 5.16: Evolution from 1971 to 2006 of world electricity generation by region (TWh). (Source: IEA, 2008).

5.4.3 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, provided there is abundance of hydro power in a region and a local goal to use H2 as fuel for transport. Hydropower can also provide the firming capacity for intermittent renewable. By storing potential energy in reservoirs, the inherent intermittent supply from intermittent renewable schemes can be supported. Peak power is expensive. The production of peak load energy from hydropower allows the optimization of base load power generation from other less flexible electricity sources such as nuclear and thermal power plants. By absorbing excess power, pumped-storage plants enable large thermal or nuclear power plants to operate at optimum output with high efficiency, even if demand is low. This contributes to reducing the GHG emissions from thermal power plants. 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 (see 5.7.1), these services can even be provided in the pumping mode of reversible turbines. [TSU: references missing]

5.4.4 Carbon credit market

There are two main project-based instruments CDM (Clean Development Mechanism) and JI (Joint Implementation). Hydropower projects are one of the largest contributors to these mechanisms and therefore to existing carbon credit markets. The United Nations Framework convention for Climate Change (UNFCCC) Executive Board (EB) has 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 arbitrary postulates and not scientific or professional documentation. The issue of methane production from reservoirs are discussed later in this chapter.

Out of the 2 062 projects registered by the CDM EB by March 1st 2010, 562 are hydropower projects (see figure 5.17). With 27% of the total number, hydro is the larger contributor. When considering the predicted volumes of carbon credits, known as Certified Emission Reduction (CERs), to be delivered, registered hydro projects are expected to avoid more than 50 million tonnes of CO2 per year by 2012, equivalent to 15% of the total. China, India, Brazil and Mexico represent roughly 75% of the hosted projects.

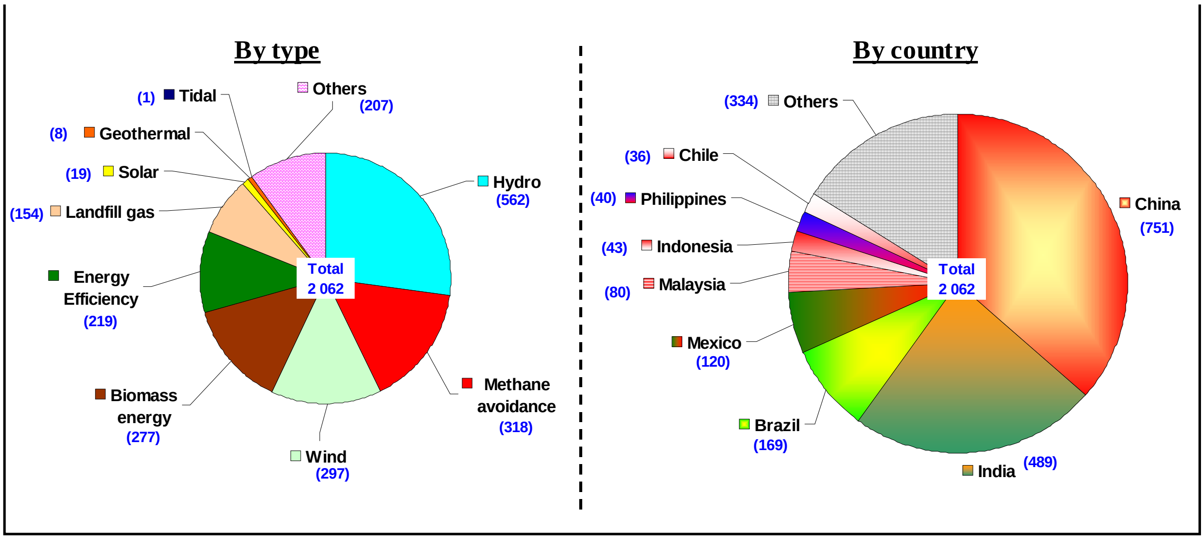


Figure 5.17: A type and country analysis of all projects registered in the CDM pipeline as on March, 1st 2010. Source: UNEP (2010) and UNFCCC (2010)

JI process is less developed today, but it is also growing. There are 114 JI registered projects on March 1st 2010, out of which 5 are hydropower (see Figure 5.18). When considering the predicted volumes of carbon credits (Emission Reduction Units-ERUs) to be delivered, registered hydro projects are expected to avoid more than 140 thousand tonnes of CO2 per year by 2012. Czech Republic and Ukraine represent more than half of those projects.

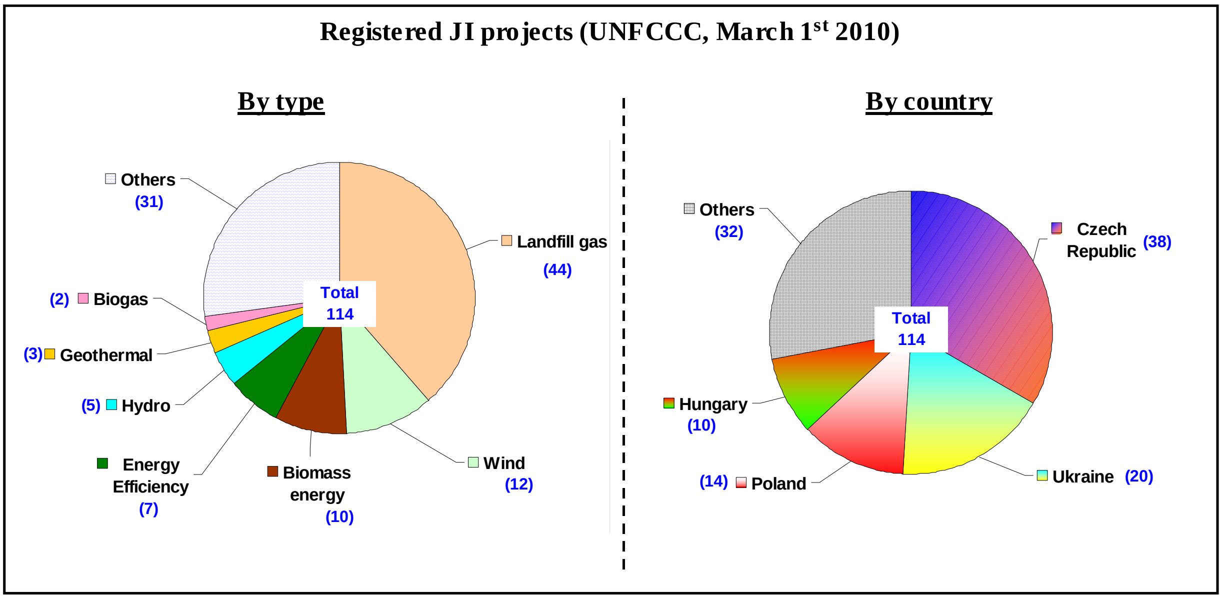


Figure 5.18: A type and country analysis of all projects registered in the JI pipeline as on March, 1st 2010 (source: UNFCCC (UNFCCC, 2010)and UNEP Risoe(UNEP, 2010).

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 capacity and above Member States must "ensure that relevant international criteria and guidelines, including those contained in the World Commission on Dams Report (see section 5.62) 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 5.6.3 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. As a result the European carbon exchanges are likely to admit CERs from hydro with a capacity over 20 MW in the near future.

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). [TSU: references missing]

5.4.5 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. 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 investment agencies 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. [TSU: references missing]

5.4.5.1 Financing

Many economically feasible hydropower projects are financially challenged. High front end costs are too often 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 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).

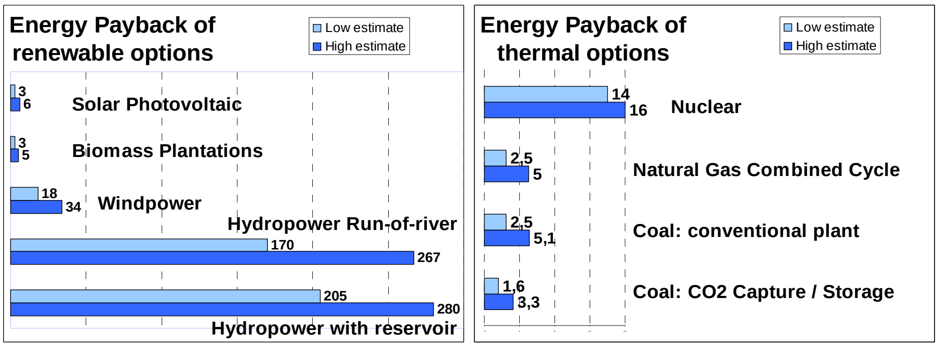


Figure 5.19: Energy Pay back Ratio (Source: Gagnon, 2008).

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.

5.4.5.2 Administrative and Licensing process

The European Union differentiates between small and large hydropower. There are different incentives used for small scale hydro[2] (feed-in tariffs, green certificates and bonus) depending on the country, but no incentives are used for large scale 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 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. 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. For Instance, the recent evolution of the relicensing process in the US in the years 2000', coming from a Traditional (TLP)

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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.

to a fully Integrated Licensing Process (ILP), where settlement agreement between stakeholders are shared early in the process to ensure that main environmental and social issues (represented by a variety of stakeholders : state env. conservation Agencies, Associations for river protection, river uses,...) have been integrated and made compatible together, before filing documents into the Administrative process (FERC, Feb. 2006) [TSU: reference missing in reference list] The environmental licence also is an important issue.

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 other non-hydro 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 power system output, increasing the economic value of the power delivered (DOE, 2004). Likewise, other renewable energy technologies 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 have extremely quick response to intermittent loads as they can be brought on stream within a few minutes 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 turbines and over 8 hours for steam turbines) 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 such as aluminium smelters and mines or individual or group of individuals.

Figure 5.20: 200 kW captive hydropower plant in Dewata Tea Estate, Indonesia. [TSU: source missing]

On the other hand rural areas may not have grids due to economic reasons and mini grid or isolated systems based hydropower , such the 200 kW captive power plant shown in figure 5.20 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 grids often faces the problem of poor plant load factor resulting in difficult financial return 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. [TSU: references missing]

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 decentralized electrification of 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 scale 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**				**Electrification rate**	**Urban electrification rate**	**Rural electrification rate**
	Total Million	**Urban** Million	**without electricity** Million	**with electricity** Million	%	%	%
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: (IEA, 2006)

Small scale 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 scale hydropower development due to their dispersed location and opportunity advantage.

- They are normally RoR schemes
- Locally 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

The development of small scale hydropower for rural areas involves social, technical and economic considerations. Local management, ownership and community participation, technology transfer and capacity building are the basic issues for success of small scale hydro plants in rural areas. [TSU: references missing]

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 in advanced/developed countries are usually found during summer daylight hours when air conditioners are running in hot weather. In northern regions the highest peak hours are usually found in the morning and in the afternoon during the coldest periods in the winter. In developing countries, where lighting is the commonest electrical device, the peak hours are usually in the evenings.

Given their operational requirements and their long startup time nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods.. Since hydroelectric generators can be started or stopped almost instantaneously, 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 technique of mixing power sources offers utility companies the flexibility to operate steam plants most efficiently as base plants while meeting peak needs with the help of hydropower and can help ensure reliable supplies and 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, 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.

From an operational standpoint hydropower is important as it needs no "ramp-up" time, as many combustion technologies do. 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 (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 coupled with its short response time allows hydropower plants to be used as storage reservoirs, 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. 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.

Storing of water is considered storage of energy and can be loosely termed as batteries for the power system. It should be emphasized however that while hydropower reservoirs store energy as a source for electricity before it is produced, pumped storage plants store electricity after it is produced. Pumped storage is normally not a source for energy. However if the upstream pumping reservoir also is used as a traditional reservoir the inflow from the watershed may balance out the energy loss caused by pumping.

Electricity already produced cannot be stored directly except by means of small capacitors and therefore has 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 in compressed air energy storage schemes (CAES) or flywheels. Various technologies for storing electricity in the grid are compared in figure 5.21.

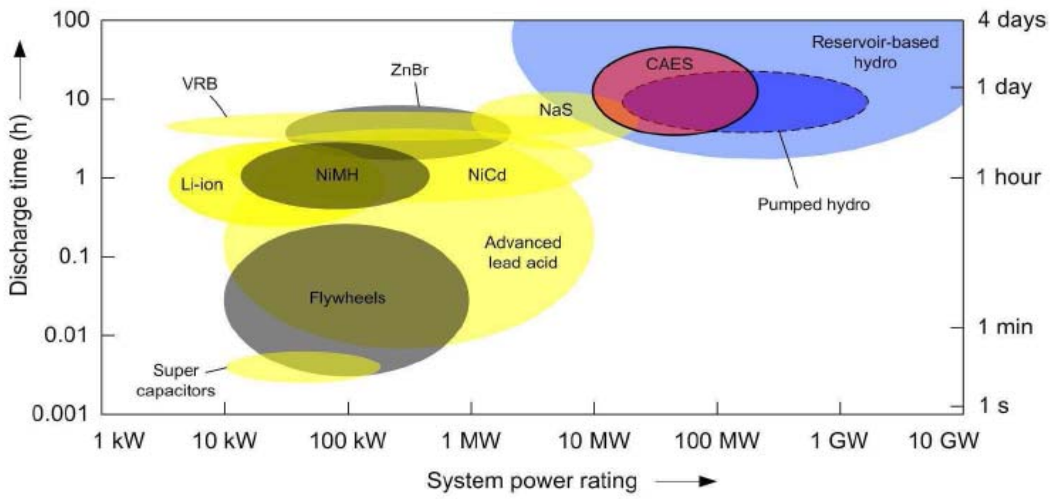

Figure 5.21: Discharge time vs. power rating of electricity storage technologies (Source: Thwaites, 2007).

Pumped storage refers to the technique where water is 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 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. Some recent projects such as Kops II in Austria also rely on ternary units (Pelton + pump on the same shaft) or separate turbines and pumps. Pumped storage is very versatile as it can be adapted in various situations to the geography of the sites and to the needs of the power systems. It is noteworthy that recent technologies allow those facilities to closely follow up the load curve MW by MW.

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. Refer to fig.5.8.

Like peaking, pumped storage keeps water in reserve for peak period power demands. 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 when needed at peak. 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. Pumped storage schemes have the same common benefits as conventional hydropower plants: flexibility and reliability. Their capacity is usually high as compared to conventional schemes, they can be used to consume excess energy during off-peak hours, for instance from intermittent sources like Wind Power. Their use and benefit in the power system depend on the mix of generating plants and the architecture of the transmission system. Pumped storage today represents 5% of the world's installed capacity. [TSU: referenced parameter not clear] Figures vary from 2.4% in the USA to nearly 9% in Japan. It is very difficult to state what should be the optimum value in a power system. It is dependent on the mix of the system, the amount of existing hydro storage facilities and on the architecture of the grid with respect to consumption load centres.

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

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.

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. [TSU: references missing]

5.5.6 Supply characteristics

Electricity markets and transmission systems have developed over the years to link large, ‘centralized’ 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 per unit of energy produced 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.

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*. Typically a hydropower plant can operate from a stopped condition to full power I just a few minutes

Example of representative international statistics can be found in table 5.4. The hydropower plants exhibit the less Equivalent Forced Outage Factor **(**EFOR).

Table 5.4: Availability Indexes.

Technology	Number Of Units (Sample)	Service Time (Years)	PLF	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

(Source: North-American-Electric-Reliability-Council).[TSU:reference year missing]

PLF	Plant Load Factor show the percent of time in a year that the station can operate at full capacity
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, give sufficient system-wide transmission capacity.

5.5.6.3 Reliability/quality

Hydroelectric power is usually extremely dispatchable and more reliable than other energy sources. Many dams can provide hundreds of megawatts within seconds to meet demand, the exact nature of the power generation availability depending on the type of plant. However the availability of power from run of river plants are dependent on the 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.

The incentivsiation of ancillary services in order to facilitate the scaling-up of electricity generation by other renewable sources of energy and smart grids is being investigated at the international policy level.

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. [TSU:references missing for whole section]

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. Itaipu Hydropower on river Parana in Brazil and Paraguay and Victoria Lake hydropower in Uganda, Tanzania and Kenya are some notable instances of regional cooperation. [TSU:references missing]

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. [TSU:point not consistent with subheading]

[TSU:references missing]

5.6 Environmental and social impacts

Like all other energy and water management options, hydropower projects do have positive and negative impacts. 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.

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

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

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 (IEA, 2000a; UNEP, 2007). By far the most effective measure is impact avoidance, weeding out less sustainable alternatives early in the design stage.

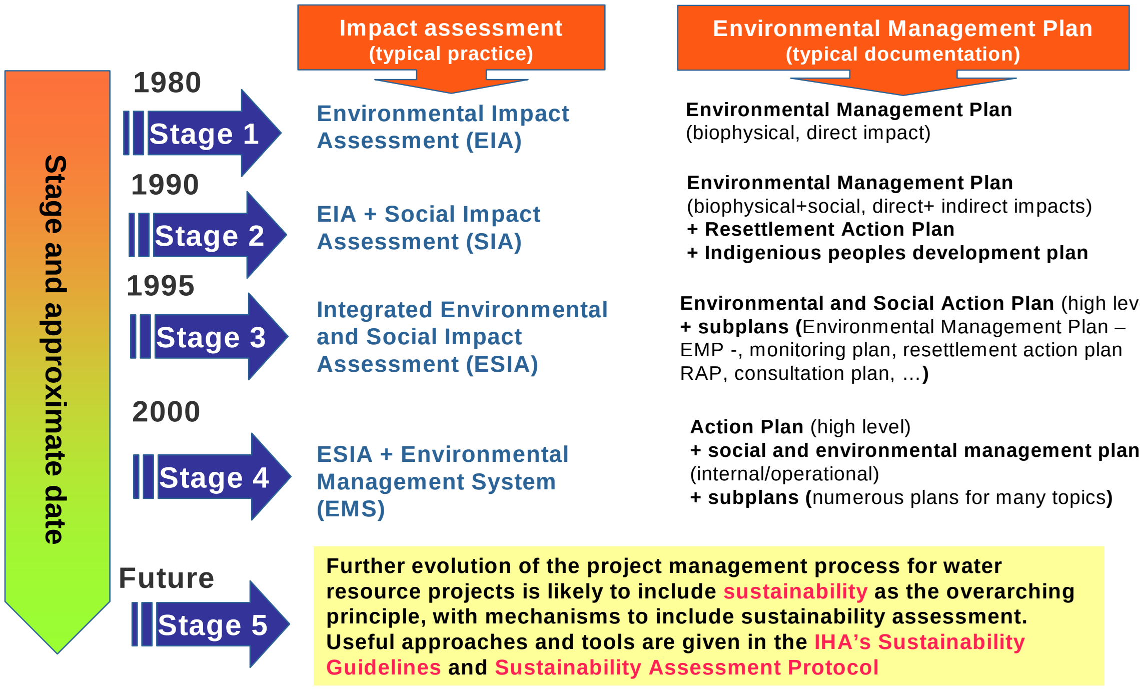

Figure 5.22: Evolution of the E&S process, adapted from UNEP (2007). [TSU: caption not clear (E&S not defined)]

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 (shifting from riverine and terrestrial to lentic ecosystem), which can have significant adverse effects according to the project's specific site conditions. Altered flow regimes, erosion and heavily impacted littoral zones in reservoirs are well known types of negative impacts (Helland-Hansen *et al.*, 2005). In addition, dams represent a barrier for fish migration (long-distance as well as local), both upwards and downwards (see below). Hydro

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

peaking operation may also affect the downstream fish populations. 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 may have 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. One of the main social impacts of HPP projects is the relocation of communities possibly living in the reservoir area, as well as impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long term and challenging task, which has been managed with variable success in the past. Large emphasis given to the physical relocation to the detriment of livelihood development is one of the main reason for these unsuccessful programs (WCD, 2000). However, as documented by Scudder (Scudder, 2005), HPPs 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 (see section 5.6.1.7).

Massive influx of workers and creation of transportation corridors also have a potential impact on environment and surrounding communities if not properly controlled and managed. In addition, workers should be in a position once demobilized at least to return to their previous activities, or to have access to other construction sites thanks to their increased capacities and experience.

According to hydropower-specific studies carried over during last 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. These have been summed up at paragraphs 5.6.1.1 to 5.6.1.11 [TSU: several of the following subsections lack references]

5.6.1.1 Hydrological Regimes

Depending on the type of hydropower project, the river flow regime is more or less modified (WCD, 2000). 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 magnitude 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 out-levelling of the annual flow pattern may affect dramatically the natural habitats changes that may have been naturally exiting in the downstream areas, prior to the project (succession of inundation and drawdown, with vegetation regrowth for instance). This may affect vegetation species and community structure, which in turn affect the mammalian and birds fauna. On the other hand, frequent (daily or weekly) fluctuations of the water level downstream a hydropower reservoir and a tailrace area might create problems both for mammals and birds. Sudden water release could drown animals and wash nests of waterfowls away. The magnitude of these changes can sometimes 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 (Scudder, 2005) 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 may be good habitat for fish. However, the impacts of reservoirs on fish species will only be perceived positive, 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 (WCD, 2000). 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. 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 2000, the WCD reported an annual loss of 0.5 to 1% of the world reservoir volume due to sedimentation. However, this phenomenon is very site specific, and tends to affect more (i) reservoirs in the lower reaches of rivers, and (ii) smaller reservoirs (WCD, 2000, p 65). In some mountainous regions like Himalayas the sediment load may however significantly reduce the life span of both the reservoir (sediment deposition) and runners (abrasion), whereas 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. Distinction of project behaviour with respect to sedimentation problems must be made between run-of-river projects on one hand and storage reservoirs on the other hand. The formers are characterized by some possibility of using flow in the upstream pond to erode and transport sediments downstream (particularly during floods), while the latter do not have the same possibility, and specific solutions must be considered.

Sedimentation has a direct influence on the maintenance costs and even on the feasibility of a HPP, and the type and volume of sediments is usually thoroughly studied during the assessment phase of any HPP project.. 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

Although existing literature related to ecological effects of river regulations on wildlife is extensive (Nilsson *et al.*, 1993; WCD, 2000), the knowledge is mainly restricted to and based on EIA studies. A restricted number of long-term studies have been carried out enabling predictions of species-specific effects of hydropower development on mammals and birds. In general four types of environmental disturbances are singled out:

- habitat changes,
- geological and climatic changes,
- direct mortality and
- increased human use of the area.

Most predictions are, however, very general and only able to focus on type of change, without quantifying the short- and long-term effects. Thus, it is generally realized that the current knowledge cannot provide a basis for precise predictions. The impacts are however highly species-, site-, seasonal -and construction-specific.

The most serious ecological effects of hydropower development to wildlife is in general

- permanent loss of habitat and special biotopes through inundation
- loss of flooding
- fluctuating water levels (and habitat change)
- aspects of landscape ecology and secondary effects

A submerged area looses all terrestrial animals, and many animals will be drowned and dispelled when a new reservoir is filled up. This can be partly mitigated through implementation of a wildlife rescue program, although it is generally recognized that these programs may have limited effect on the wild populations on the long term (WCD, 2000; Ledec *et al.*, 2003). Endangered species attached to specific biotopes require particular attention and dedicated management programs prior to impoundment. Increased aquatic production caused by nutrient leakage from the inundated soil immediately after damming, have been observed to affect both invertebrates and vertebrates positively for some time, i.e. until the soil nutrients have been washed out. An increase in aquatic birds associated with this damming effect in the reservoir has been observed.

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. Solutions for upstream fish migrations are now pretty well managed: a variety of solutions have been tested for the last 30 years and have shown acceptable to high efficiency. Fish ladders can partly restore the upstream migration, but they must be carefully designed, and well suited to the site and species considered (Larinier *et al.*, 2004)). In particular they may not be adapted to high head schemes. Conversely, downstream fish migration remains more difficult to address. Most fish injuries or mortalities during downstream movement are due to their passage through turbines and spillways. In low-head HPPs, improvement in turbine design (“Fish Friendly Turbines”), spillway design or overflow design has proven to successfully reduce fish injury or mortality rates, especially for eels, and to a lesser extent salmonids (Amaral et al., 2009). [TSU: reference missing in reference list] 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 (WCD, 2000; Scudder, 2005). 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 reservoir 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. Ratio of anthropogenic vs natural emissions of mercury is difficult to assess, although it is now considered that two thirds of mercury in global fluxes is from anthropogenic sources (Hoffman *et al.*, 2003). In some areas human activities like coal burning (North America) and mining represent a significant contributor. 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 (Bank, 1994). 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[5] 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[6], seven strategic priorities[7] 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 (Bank, 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

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

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

[7] 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

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 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 (IHA, 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.

Guidelines are key tools to manage E&S impacts, but they will need to be adapted to the specific context of each particular project (IHA, 2006). National regulations issued from such international guidelines should be writing in a way to promote sustainable hydropower development "The report is not intended as a blueprint" (WCD, 2000).

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. These emissions are not considered to be important for the whole life cycle of the reservoir. Furthermore, emissions associated with land use change (including deforestation, agricultural practices, and urbanisation) have to be approached with care, as they are not always a direct consequence of the dam construction.

- **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 studied projects are multipurpose projects. Yet, a study carried out by IEA (2000b) based on LCA and later published in Energy Policy (EIA, 2002), mentioned that the amount of CO_2 – equivalent emitted by hydropower is around 15g CO2eq/kWh or less (VGB-Power-Tech, 2009). 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 24 countries (Tremblay *et al.*, 2005) have lead to the following conclusions:

- All freshwater systems, whether they are natural or manmade, emit greenhouse gases (GHG) due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHG. They also bury some carbon in the sediments (Cole *et al.*, 2007).
- Within a given region that shares similar ecological conditions, reservoirs and natural water systems produce similar levels of CO_2 emissions per unit area. In some cases, natural water bodies and freshwater reservoirs even absorb more CO_2 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 terrestrial ecosystem, wetlands, rivers and lakes that were located in the area before impoundment and abstract the effect of carbon inflow from the terrestrial ecosystem, both natural and related to human activities, on the net GHG emission before and after impoundment..

The main GHG produced in freshwater systems are carbon dioxide (CO_2,) and methane (CH_4). The nitrous oxide (N2O) could be also an issue in some cases and more particularly in reservoirs with large drawdown zones or in tropical areas. 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.*, 2008).

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. 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). 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 when methanotrophic bacteria are present. 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.

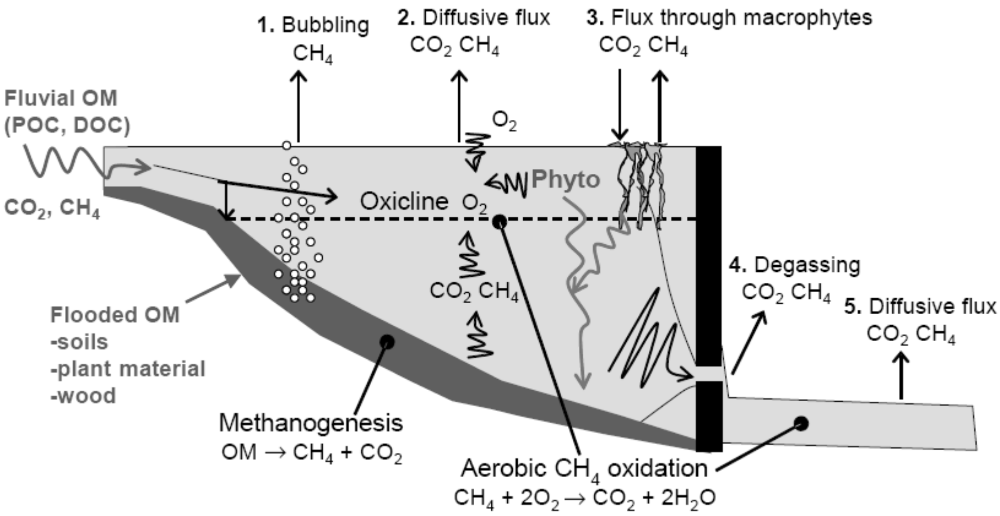

Figure 5.23: Carbon dioxide and methane pathways in freshwater reservoir with an anoxic hypolimnion (e.g. Guerin et al., 2008).

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 fluxes have been investigated in boreal (e.g. Rudd *et al.*, 1993; Tremblay *et al.*, 2005), temperate (Casper *et al.*, 2000; Soumis *et al.*, 2004; Therrien *et al.*, 2005) and tropical/subtropical (e.g. Guerin *et al.*, 2008) regions. Gross emissions measurements in are summarized in Table 5.5. below.

Table 5.5: Range Of Gross CO_2 And CH_4 Emissions From Hydroelectric Freshwater Reservoirs. [TSU: source missing]

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})

Numbers in parentheses are the number of studied reservoirs (UNESCO-RED, 2008). [TSU: include sentence in table caption]

Gross emissions measurements in boreal and temperate regions from Canada, Finland, Iceland, Norway, Sweden and USA imply that highly variable results can be obtained for CO_2 emissions, so that reservoirs can act as sinks, but also can present significant CO_2 emissions. Significant CH_4 emissions were not observed in these studies (under boreal/temperate conditions, significant CH_4

emissions are expected only for reservoirs with large drawdown zones and high organic and nutrient inflows).

In tropical regions, high temperatures coupled with important demand in oxygen due to the degradation of substantial Organic Matter (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 and soil organic carbon with different absolute and relative values (Galy-Lacaux *et al.*, 1999; Blais *et al.*, 2005; Descloux *et al.*, 2010).

According to UNESCO/IHA (2008) measurements of gross emissions have been taken in the tropics at four Amazonian locations[8] and additional sites in central and southern Brazil[9]. They have shown, in some cases, high gross GHG emissions. 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[10]. 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 or by internal processes in the reservoir. In boreal and temperate conditions, GHG emissions have been observed to return to the levels found in neighbouring natural lakes after the 2-4 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-RED, 2008)[11].

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.

The project will present a measurement specification guidance in July 2010 to enable standardised measurements and calculations worldwide, and aims at delivering a database of results and characteristics of the measurement specification guidance being applied to a representative set of reservoirs worldwide. The final outcome will be building predictive modelling tools to assess the GHG status of unmonitored reservoirs and new reservoir sites, and guidance on mitigation for vulnerable sites.

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

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

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

[11] More information can be found at http://www.hydropower.org/climate_initiatives.html. [TSU: URL in text]

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 *et al.*, 2003). According to the WCD's Final Report (WCD, 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 (WB, 2005), [TSU: reference missing in reference list] 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 optimized 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 corrosion and cavitation. 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 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. Use of Computational Fluid Dynamics (CFD) is an important tool, making it possible to design turbines with high efficiency over a broad range. Other techniques like artificial intelligence, neural networks, fuzzy logic and genetic algorithms are increasingly used to improve operation and reducing cost of maintenance of hydropower equipment.

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 scale hydropower potential (<10 MW) was previously assumed to be 7 TWh. A new study initiated in 2002-2004, revealed this potential to be nearly 25 TWh at a cost below 0.06 US$/kWh and 32 TWh at a cost below 0.09 US$/kWh (Jensen, 2009) [TSU:convert to US $ 2005].

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 in comparison to a fixed-speed plant have been found in simulation studies (Terens *et al.*, 1993) (Fraile *et al.*, 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, already well accepted, 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 low-head 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's most practical application in the near term is likely to be in rivers and streams. Hydrokinetic turbines have low energy density.

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).

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.”

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.

5.7.5 New materials

Major wearing effects on hydropower equipment are corrosion, cavitation damages and abrasion. An intensified use of suitable proven materials such as stainless steel and the invention of new developments as coatings limit the wear on equipment and extend lifespan. Improvements in material development have been performed for almost any plant component. Examples are: a) penstocks made of fiberglass; b) better corrosion protection systems for hydro-mechanical equipment; c) better understanding of electrochemical corrosion leading to a suitable material combination; d) trash rack systems with plastic slide rails.

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). The problem may also become more important in case of increased peaking.

Modern turbine design using 3D-flow-simulation provides not only better efficiencies in energy conversion by improved shape of turbine runner and guide/stay vanes. It also leads to a decrease of cavitation damages at high head power plants and to reduced abrasion effects when dealing with heavy sediment loaded propulsion water. Other inventions concern e.g. improved self lubricating bearings with lower damage potential and the invention of electrical servo motors instead of hydraulic ones.

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 [TSU: state currency as US $ 2005, depending on origin consider converting the figure] 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 multipurpose dams and better planning tools for multipurpose 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 hydropower generation potential has been described in section 5.2.1, where the global technical potential was given as 14368 TWh/year, and the developed hydropower system 2794 TWh/year per

2005. The cost of project implementation for remaining hydropower will vary a lot from project to project, so a general estimate is difficult to give. A number of studies have been published, however, and a summary of findings and conclusions from the most relevant studies are given below. The most important data are summarized in Table 5.6.

Table 5.6: Cost projection for Hydropower investment in different studies [TSU: give reference year for Greenpeace/EREC]

Source	Investment cost in US $/KW	O&M cost in %	Full load hours	Energy cost in cent/KWh	Comments
WEA 2004	1000 - 3500 $/KW			2 - 8	No trend - future cost same as those in 2004
					Energy cost calculated here based on
IEA-WEO 2008	2184 $/KW in 2005	2.5		*7.1*	*10% interest rate*
	2194 $/KW in 2030	2.5		*7.1*	*Load factor 0.45*
	2202 $/KW in 2050	2.5		*7.1*	*40 year depreciation period*
IEA-ETP 2008	1000-5500 $/KW in 2005	2.2 - 3			
	1000-5400 $/KW in 2030	2.2 - 3			
	1000-5100 $/KW in 2050	2.2 - 3			
IEA-2010	750-19000 $/KW in 2010			*2.3 - 45.9*	13 projects from 0.3 to 18000 MW
	1278 $/KW in 2010		4470	4.8	Weighted average all projects
VLEEM-2003	500-4500 $/KW				240 Projects commisioned from 2002-2020
Lako et al 2003	1000 $/KW				Weighted average all projects
	90% below 1600 $/KW				
					Energy cost calculated here based on
Greenpeace/EREC	2880 $/KW in 2010	4		*10.4*	*10% interest rate*
	3200 $/KW in 2030	4		*11.5*	*Load factor 0.45*
	3420 $/KW in 2050	4		*12.3*	*40 year depreciation period*
BMU Lead Study 2008	2440 $/KW in 2005			7.3	6 % Interest rate used in the study
	3125 $/KWin 2030			8.5	
	3125 $/KW in 2050			8.0	
Krewitt et al 2009	1000-5500 $/KW in 2005				30 year depreciation period is used in this study
	2000	4	2900	9.8	Indicative estimate (average)
	1000-5400 $/KW in 2030				
	2200	4	2900	10.8	Indicative estimate (average)
	1000-5100 $/KW in 2050				
	2500	4	2900	11.9	Indicative estimate (average)

World Energy Assessment (WEA) was first published in 2000 by UNDP and World Energy Council. This study has later been widely used and is being referred to by many later studies. The original report was updated in 2004 (UNDP/UNDESA/WEC, 2004)) and it is this version of the report that is used here. The 2004 report gives an estimate of both theoretical potential for hydropower (40 500 TWh/year or 147 EJ/year), technical exploitable potential (14 320 TWh/year or 50 EJ/year) and economic potential (8100 TWh/year). Unfortunately, the definition of what is considered economic accessible is not defined precisely. The report gives cost estimates both for current and future hydropower development. The cost estimates are given both as turnkey investment cost in US$ pr kW and as energy cost in US cents per kWh. Both cost estimates and capacity factors are given as a range with separate values for small and large hydropower. After a discussion of factors contributing to increasing future cost (mostly environmental and social factors) and factors contributing to decreasing cost (various technological innovations), the conclusion is that these factors probably balance each other, and it is difficult to see any clear trend up or down. Future cost for large hydropower (96.5% of all) is expected to be in the range of 2 to 8 cent per kWh, for small hydro (3.5% of all) [TSU: referenced parameter not clear] it is expected to be in the range 3 to 10 cent per kWh in the future. Since large hydro is dominating both in the present and future system, it will be most correct to focus on the large hydro cost values.

Very Long Term Energy-Environment Model (VLEEM) was an EU-funded project executed by a number of research institutions in France, Germany, Austria and Netherland. Of the many interesting reports from this project, we will focus on "Hydropower Development with a Focus on Asia and Western Europe" (Lako et al., 2003).

This report contains very detailed information, including cost estimates, for 240 hydropower projects worldwide, with most in-depth focus on Asia and Western Europe. The projects were planned for commissioning between 2002 and 2020. A key result from this report is the distribution of investment cost vis-à-vis cumulative capacity for different regions and countries. A summary of cost estimates for the projects were compiled and is presented in Figure 5.24.

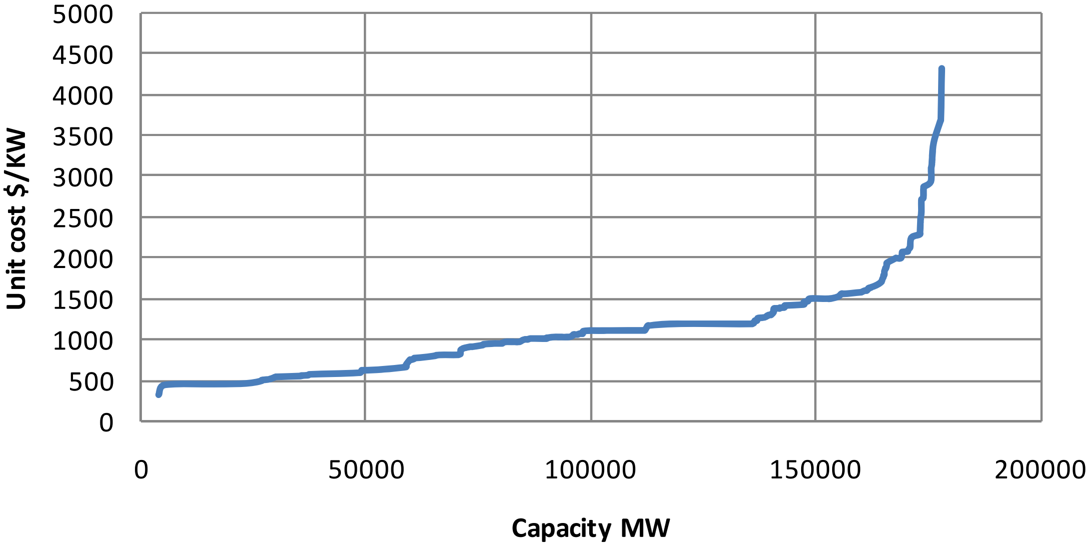

Figure 5.24: Distribution of unit cost ($/kW) for 190 hydropower project sites studied in the VLEEM project. (Source: Hall et al., 2003). [TSU: convert to US $ 2005]

REN21 - "Renewable Energy Potentials - Opportunities for the rapid deployment of renewable energy in large energy economies" was published in 2008 (REN21, 2008). Hydropower is studied in a special report "Global potential of renewable energy sources: A literature assessment". In this report data can be found both for assumed hydropower potential and cost of development for remaining potential. Data seem to come mostly from UNDP/UNDESA/WEC, 2000.

European Renewable Energy Council (EREC) and Greenpeace presented a study in 2008 called "Energy [R]evolution: A Sustainable World Energy Outlook" The report presents a global energy scenario with increasing use of renewable energy, in particular wind and solar energy. The report contains a detailed analysis up to 2050 and perspectives beyond, up to 2100. Also hydropower is included and future scenarios for cost are given from 2008 up to 2050.(EREC,2008)

BMU Lead Study 2008 - "Further development of the strategy to increase the use of renewable energies within the context of the current climate protection goals of Germany and Europe" was commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and published in October 2008. It contains estimated cost for hydropower development up to 2050.

IEA (International Energy Agency) have published several very important reports recently, "World Energy Outlook 2008", "Energy Technology Perspective 2008" and "Projected cost of generating electricity 2010 Edition" where cost data can be found both for existing and future hydropower projects.

Krewitt et al (2009) reviewed and summarized findings from a number of studies from 2000 till 2008. The main source of data for future cost estimates were (UNDP/UNDESA/WEC, 2000; Lako *et al.*, 2003; UNDP/UNDESA/WEC, 2004; IEA, 2008) (EREC, 2008).

Hall *et al.* (2003) published a study for USA where 2155 sites with a total potential capacity of 43 000 MW were examined and classified according to unit cost. The distribution curve shows unit costs that varies from less than 500 $/kW up to over 6000 $/kW [TSU: convert to US $ 2005] (Figure 5.25). Except from a few projects with very high cost, the distribution curve is nearly linear, for up to 95% of the projects. Development cost of hydropower include cost on Licensing, Plant construction, Fish and wildlife mitigation, Recreation mitigation, Historical and archaeological mitigation and Water quality monitoring cost.

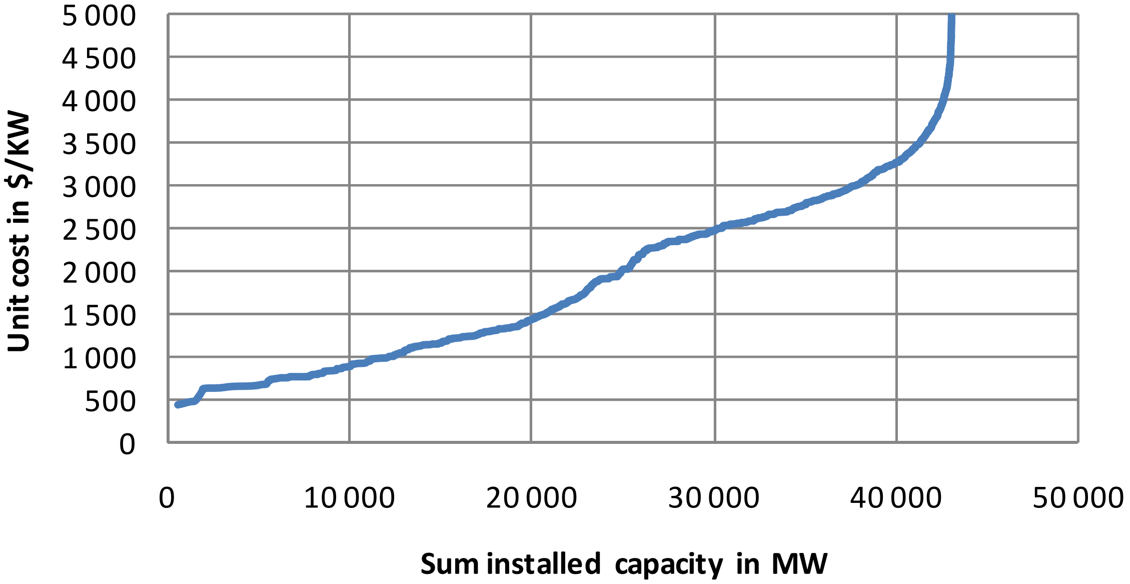

Figure 5.25: Distribution of unit cost ($/kW) for 2155 hydropower project sites studied in USA. (Source: Hall et al., 2003). [TSU: convert to US $ 2005]

Results from all these different studies are summarized in Table 5.6. Most important cost parameters are Investment cost ($/kW) and levelized cost of energy (LCOE) in cent/kWh.

The calculation of LCOE includes a number of parameters, beside investment costs, and a careful selection of these are needed to get a correct result. Most important are Load factor, Operation and Maintenance costs (O&M costs), Depreciation period and Interest rate.

For intermittent energy sources like wind, water and waves, the statistical distribution of the resource will determine the load factor. A low load factor gives low production and higher levelized cost for the energy. Krewitt *et al.* (2009) used a very low value, 2900 hours or 33% while for example IEA 2010 (IEA, 2010) found an average of 4470 hours or 51%. By analyzing energy statistics from IEA we find that typical load factors for existing hydropower systems are in the range from 37% to 56% (USA 37%, China 42%, India 41%, Russia 43%, Norway 49%, Brazil 56%, Canada 56%). We suggest that an average load factor of 45% will be most correct for future hydropower developments.

Operation and Maintenance cost (O&M-cost). Once built and put in operation, hydropower usually requires very little maintenance and operation costs can be kept low. O&M costs are usually given as % of investment cost per kW. Greenpeace/EREC Krewitt *et al.* (2009) used 4% . This may be appropriate for small hydro but is probably too high for large hydropower plants. IEA-WEO 2008 used 2.5%. IEA-ETP 2009 used 2.2% for large hydro increasing to 3% for smaller and more expensive projects. We suggest to use 2.5% as a typical value for O&M cost for future hydropower development.

Depreciation period is the number of years ("Lifetime") the station is expected to be fully operational and contributing to production and income. For hydropower, and in particular large hydropower, the largest cost components are civil structures with very long lifetime, like dams, tunnels, canals etc. Electrical and mechanical equipment, with much shorter lifetime, usually contributes less to the cost. It is therefore common to use a much longer depreciation period for hydropower that for example wind or wave power where most of the cost is connected to E&M equipment. Krewitt *et al.* (2009) used 30 years for hydropower and 20 years for wind and wave technology. The IEA-2010 study use 80 years for hydropower, 20 years for wave and tidal plants and 25 years for wind and solar plant. We suggest 40 years as a reasonable value, this may be too low for large hydro but ok for small hydro.

Interest rate on investment is a critical parameter, in particular for renewable technologies where the initial investment costs dominates in the calculation of energy cost. A high interest rate will be beneficial for technologies with low initial investment and high running costs, like coal and gas fired power plants. A low interest rate will favor renewable technologies, and in particular technologies with long lifetime like hydropower. In some of the studies it is not stated clearly what interest rate that has been used. BMU Lead Study 2008 used 6%. In IEA-2010 energy costs were computed both for 5% and 10% interest rate. For hydropower an increase from 5% to 10% gives an increase in energy cost of nearly 100%. We have calculated energy cost for two alternatives, a low (6%) and a high (10%).

5.8.2 Future cost of hydropower

There is still a large untapped potential for new hydropower development up to the assumed economic potential of between 8000 and 9000 TWh/year. Since all hydropower projects are site-specific, the untapped potential includes projects with varying cost, ranging from below 500 $/kW up to 10000 $/kW and even higher [TSU: state US$2005 instead of US$; depending on origin consider converting this figure]. The exact cost for all possible projects is not well known, but an estimate of the variability can be seen from the range of cost given for example in UNDP/UNDESA/WEC (2000; 2004) and IEA (2010) (Table 5.6) and in more detail from the two studies summarized in Figure 5.24 and 5.25 It is reasonable to assume that in general projects with low cost will be developed first, and as the best projects have been developed, increasingly costly projects will be used. Very expensive project will usually have to wait and possibly be used at a later stage. But there are many barriers and the selection of the "cheapest projects first" may not always be possible. In Europe, for example, small hydro with rather high cost is now being developed (IEA, 2010) at very high cost, but still favorable compared to other alternatives.

Estimates of potential deployment of new hydropower up to 2030 (Ch. 5.9) is in the order of 2000-3000 TWh/year, still far below the economic potential. Considering the cost structure distribution for mostly large projects (Figure 5.6) and mixture of small and medium size projects (Figure 5.YY) [TSU: reference inexistent], it seem reasonable to assume a gradually increasing cost from today and up to 2050. A typical investment cost can be 1500 $/kWh in 2010, increasing to 2000 $/kWh in 2030 and 2500 $/kWh in 2050 [TSU: convert to US $ 2005], as the more favorable projects have been developed. Using these figures and assumptions regarding Load factor, O&M cost, Depreciation time and Interest rate as discussed before, cost trends for hydropower can be computed from now up to 2050. The results are given in Table 5.7

Table 5.7: Cost projection for hydropower investment – suggested values by SRREN

Interest rate/Depreciation	Investment cost in US$/kW	O&M cost in %	Full load hours	LCOE cent/kWh	Comments
3% interest rate	1500 $/kW in	2.5%	3950	2.6	Projects with lowest cost

40 year depreciation period	2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5%	3950 3950	3.5 4.3	implemented first Increasing cost for remaining projects
7% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	3.8 5.1 6.3	Projects with lowest cost implemented first Increasing cost for remaining projects
10% interest rate 40 year depreciation period	1500 $/kW in 2010 2000 $/kW in 2020 2500 $/kW in 2050	2.5% 2.5% 2.5%	3950 3950 3950	4.8 6.4 8.1	Projects with lowest cost implemented first Increasing cost for remaining projects

The results clearly show the importance of the interest rate. With a low interest rate of 6% [TSU: reconcile with table 5.7 reporting 3,7 and 10% interest rate] the energy cost from hydropower will increase from 3.5 c/kWh in 2010 up to 5.8 c/kWh in 2050. With a higher interest rate of 10%, the typical hydropower energy cost will increase from 4.8 c/kWh today up to 8.1 c/kWh in 2050.

These values are well within the range of cost estimates given by UNDP/UNDESA/WEC (2000; 2004) and the various analyses published by IEA, but much lower than the values found by EREC (2008) and (Krewitt, 2009). The energy cost for hydropower in these two analyses are very high due to an unfavorable combination of assumptions regarding initial investment cost, O&M cost, depreciation time and interest rate.

Development cost of hydropower and also cost per unit of energy produced, depend on licensing, plant construction, fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation and water quality monitoring cost. Hall *et al*. (2003) in their study also presents typical plant construction cost for new sites according to Fig 5.26.

Basically, there are two major cost groups: the civil construction costs, which normally are greater costs of the hydropower project, and those that have to do with electromechanical equipment for energy transformation. The civil construction costs follow the price trend of 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 construction materials for civil works

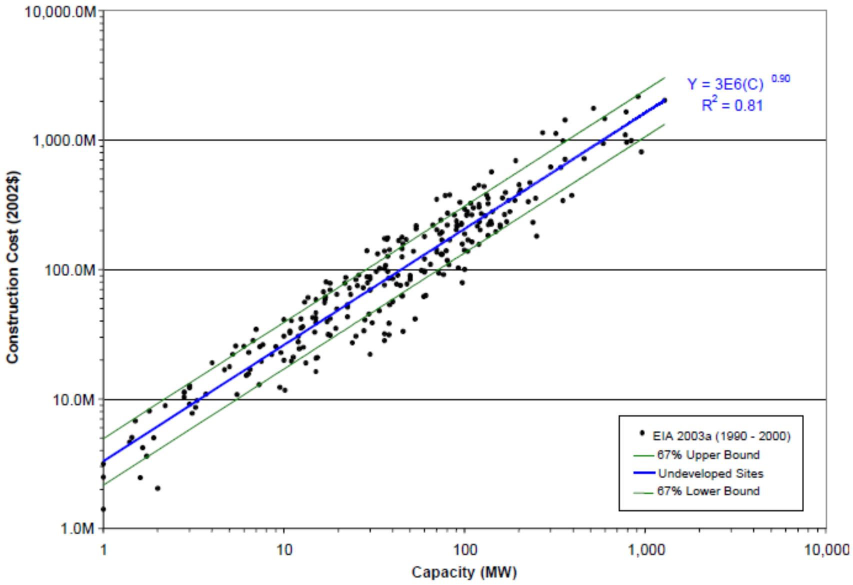

Figure 5.26: Hydropower cost as a function of plant capacity for new sites. [TSU: source missing, convert to US $ 2005]

The costs of electromechanical equipment follow the global prices for these components, except in the countries, where most of the machinery used in the hydropower projects is produced, and where prices are more stable. 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,) presents the cost of electromechanical equipment from various hydroelectric projects as given in Figure 5.27.

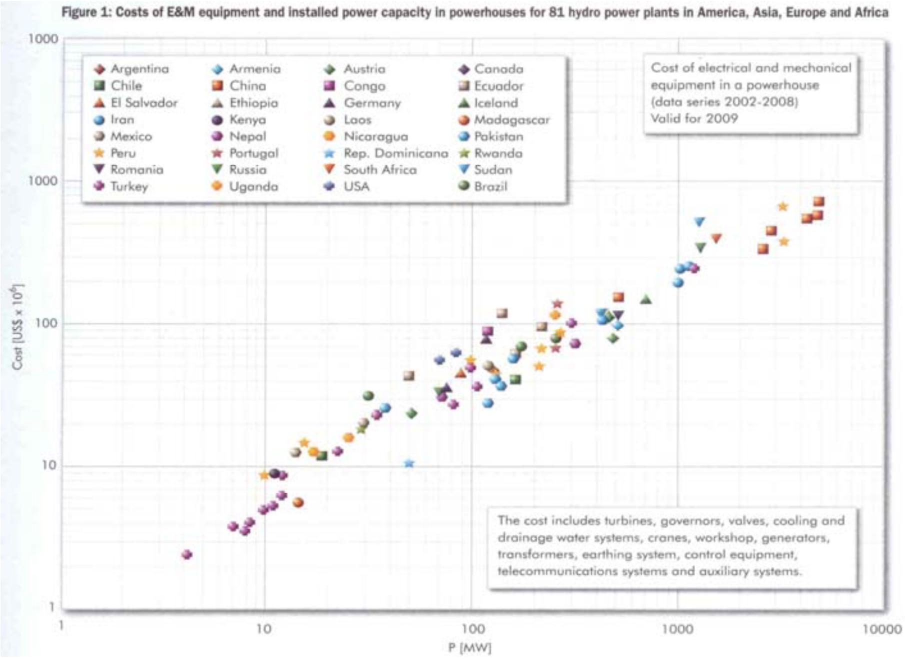

Figure 5.27: Costs of electrical and mechanical (E&M) equipment and installed power capacity in powerhouses for 81 hydro power plants in America, Asia, Europe and Africa. (Source: Avarado-Anchieta (2009,) [TSU: readability, convert to US $ 2005]

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 are generally 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.

5.8.3 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 carry out at its separable cost. Separable cost for any purpose is obtained by subtracting 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 the last decade the reservoirs were mostly funded and owned by the public sector, thus project profitability 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 Czechoslovakia 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). The Government of India later adopted the use-of-facilities method for allocation of joint costs of multipurpose river valley projects (Jain, 2007).

The issue of estimating costs and projections is not an obstacle for the development of hydroelectricity as a renewable resource.

5.9 Potential deployment

Hydropower offers significant potential for near- and long-term carbon emissions reduction. The hydro capacity installed by the end of 2008 delivers roughly 16% of worldwide electricity supply: hydropower is by far the largest RES in the electricity sector (hydro represents 86% of RE electricity). On a global basis, the hydro resource is unlikely to constrain further development (section 5.2). Hydropower technology is already being deployed at a rapid pace (Sections 5.3 and 5.4), therefore offering an immediate option for reducing carbon emission in the electricity sector. With good conditions, the cost of hydro energy can be less than USD 0.02/kWh (see section 5.8). Hydropower is a mature technology and is at the cross-roads of 2 major issues for a country development: water and energy. This provides hydro a key role for both energy and water security.

This section begins by highlighting near-term forecasts for hydro deployment (5.9.1). It then discusses the prospects for and potential barriers to hydro deployment in the longer-term and the potential role of that deployment in meeting various GHG mitigation targets (5.9.2). Both subsections are largely based on energy-market forecasts and carbon and energy scenarios literature published in the 2007-2009 time period.

5.9.1 Near-term forecasts

The continuing rapid increase in hydro capacity from the last 10 years is expected by many studies to continue in the near- to medium-term (see Table 5.8). Much of the world increase in renewable electricity supply is fuelled by hydropower and wind power. Hydro is economically competitive with fossil fuels over the projection period. From the 923 GW of hydro capacity installed at the end of 2007, the International Energy Agency (IEA, 2009) and U.S. Energy Information Administration (IEA, 2009) reference-case forecasts predict growth to 1,099 GW and 1,047 GW by 2015 respectively (e.g. additional 22 GW/annum and 30 GW/annum by 2015 respectively).

Table 5.8: Near-Term Hydro Energy Forecasts

Study	Hydro situation				Hydro forecast in 2015		
	Reference year	Installed capacity (GW)	Electricity generation (TWh)	% of global electricity supply	Installed capacity (GW)	Electricity generation (TWh)	% of global electricity supply
IEA (2009a)	2007	923	3 078	16%	1 099	3 692	15%
U.S. EIA (2009)	2006	776	2 997	17%	1 047	3 887	17%

Non-OECD countries, and in particular Asia (China and India) and Latin America, are projected to lead in hydro additions over this period. In 2008, it should be noted that 40 GW of new hydropower has been put in operation.

5.9.2 Long-term deployment in the context of carbon mitigation

The IPCC's Fourth Assessment Report (AR4) assumed that hydro could contribute 15% of global electricity supply by 2030, or 4,300 TWh/year (~ 15.5 EJ) (IPCC, 2007b). This figure is lower than some commonly cited business-as-usual case. The IEA's World Energy Outlook 2009 reference case, for example predicts 4,680 TWh/year of hydro by 2030, or 14% of global electricity supply (IEA, 2009). The US EIA forecasts 4,780 TWh/year of hydro in its 2030 reference case projection, or 15% of net electricity production (IEA, 2009).

It should be noted that the IEA's World Energy Outlook 2008 presents, in addition to the reference case, 2 scenarios regarding the context of carbon mitigation (IEA, 2008). The table 5.9 summarizes these results. In the most stringent 450 ppm stabilization scenarios in 2030, installed capacity of new hydro increases by 545 GW compared to the reference case (e.g. approximately +40%). This study highlights that there is an increase in hydro supply with increasingly aggressive GHG targets.

Hydro can increase annually by roughly 5% in the lowest carbon concentration scenario (e.g. 450 ppm) by 2030.

Table 5.9: Long-term hydro deployment scenarios in the context of carbon mitigation according to IEA forecasts

Hydro installed capacity in GW, in regards to CO2 concentration (IEA, 2008)	**2006**	**2020**	**2030**	**Average annual increase (GW/year)**	**Average annual increase (%/year)**
Reference case scenario	**919**	**1 239**	**1 436**	**22**	**2.3%**
550 ppm scenario		**1 409**	**1 659**	**31**	**3.4%**
450 ppm scenario		**1 409**	**1 981**	**44**	**4.8%**

The figure 5.28 summarizes the different scenarios for hydropower generation in 2020 and 2030. For instance in 2030, the hydropower can generate annually between 4680 TWh (IEA, 2009)and 6454 TWh (IEA, 2008) depending on carbon mitigation scenarios.

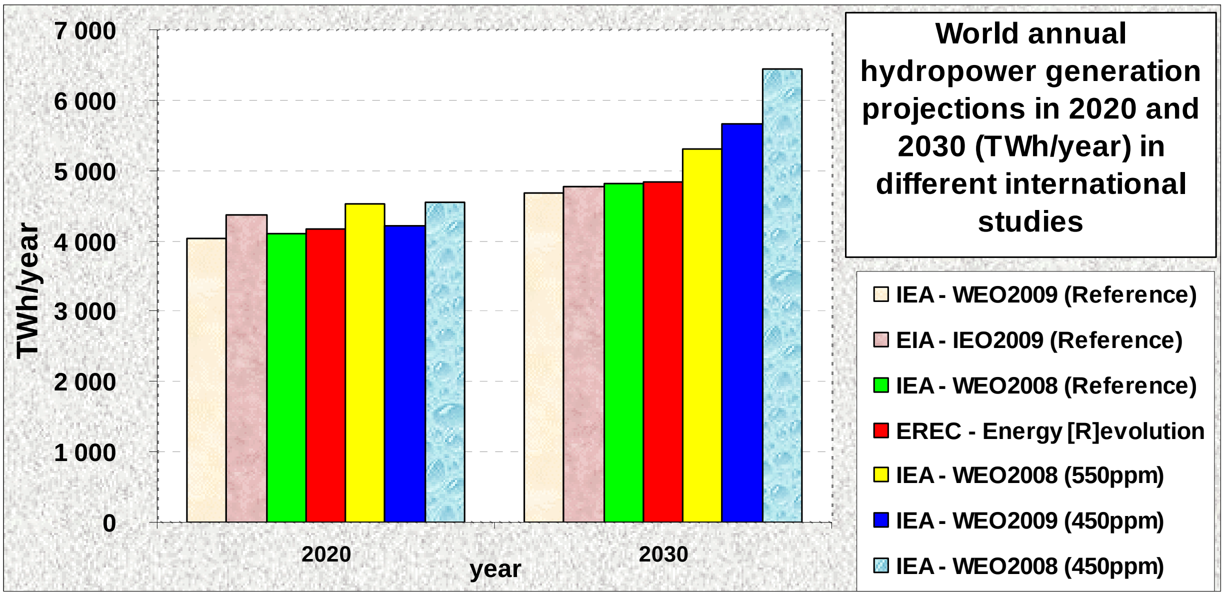

Figure 5.28: Hydro deployment scenarios for the year 2020 and 2030 from different studies

A summary of the literature on the possible contribution of RE supplies meeting global energy needs under a range of CO2 stabilization scenarios is provided in Chapter 10. Focusing specially on hydro, Figures 5.29 present modelling results on the global supply of hydro (in EJ and as a percent of global electricity demand, respectively) ; refer to Chapter 10 for a full description of this literature.

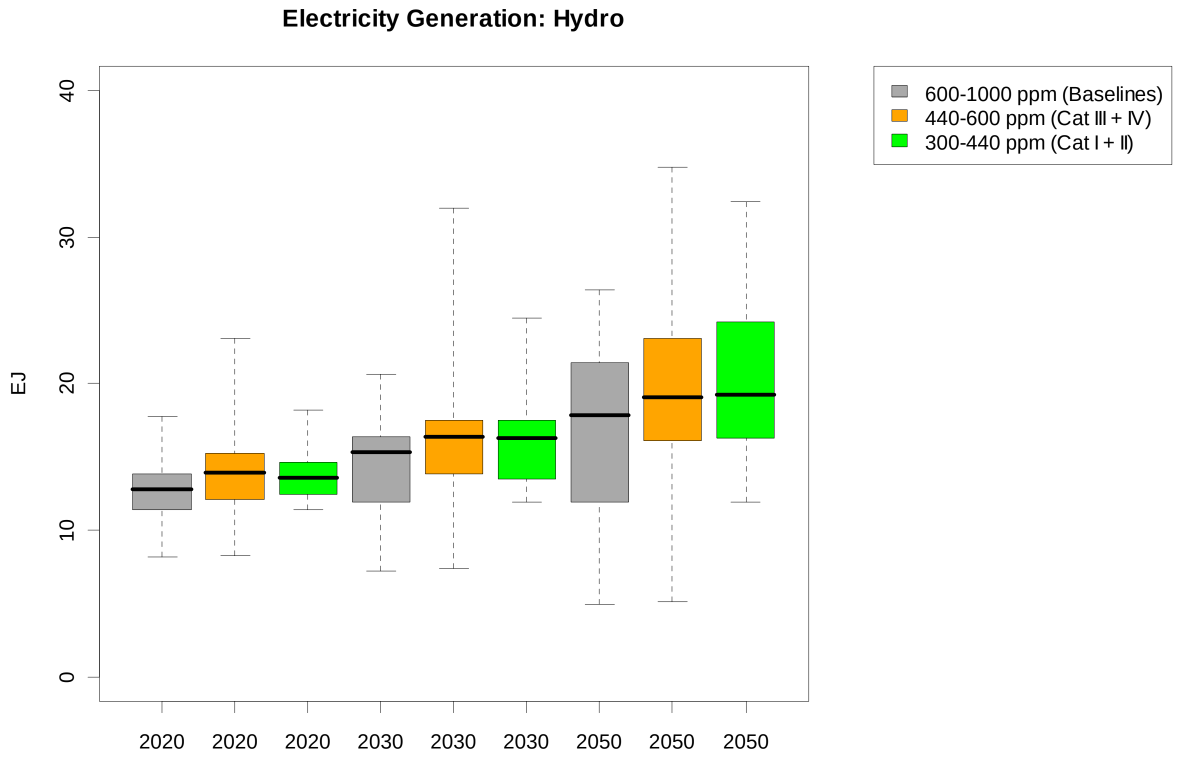

Figure 5.29: Global supply of hydro in carbon stabilization scenarios (median, 25th to 75th percentile range, and absolute range) [TSU: adapted from Krey and Clarke, 2010 (source will have to be included in reference list); see also Chapter 10.2]

The reference-case projections of hydro's role in global energy supply span a broad range, but with a median of roughly 13 EJ in 2020, 16 EJ in 2030 and 19 EJ in 2050 (Figure 5.29). Substantial growth of hydro is therefore projected to occur even in the absence of GHG mitigation policies, with hydro median contribution to global electricity supply maintaining its share at around 15%. Therefore hydro remains the main RES technology. The contribution of hydro grows as GHG mitigation policies are assumed to become more stringent: by 2030, hydro's median contribution equals roughly 16.5 EJ (e.g. x% of global electricity supply) in the 440-600 and 300-400 ppm-CO2 stabilization ranges, increasing to 19-20 EJ by 2050 (~% of global electricity supply).

The diversity of approaches and assumptions used to generate these scenarios is great, however, resulting in a wide range of findings. Reference case results for hydro supply in 2050 range from 5-26 EJ (median 18 EJ), or x-y% (median of z%) of global electricity supply. In the most stringent 200-440 ppm stabilization scenarios, hydro supply in 2050 ranges from 12-32 EJ (median 20 EJ), equivalent to x-y% (median of z%) [TSU:values missing] of global electricity supply.

Despite this wide range, hydro has the lowest range compared to all other renewable energy sources. IPCC-2007a estimate for potential hydro supply of around 16 EJ (+/- 0.5 EJ) by 2030 appears conservative compared to the more-recent scenarios literature presented above, can reach 24 EJ in 2030 for the 450 ppm scenario (IEA, 2008).

Though the literature summarized in Figures 5.29 shows an increase in hydro supply with increasingly aggressive GHG targets, that impact is not great as it is for biomass, geothermal, and solar energy, where increasingly stringent carbon stabilization ranges lead to more-dramatic increases in technology deployment (Chapter 10). One explanation for this result is that hydro is already mature and economically competitive; as a result, deployment is predicted to proceed rapidly even in the absence of aggressive efforts to reduce carbon emissions.

The scenarios literature also shows that hydro could play a significant long-term role in reducing global carbon emissions: by 2050, the median contribution of hydro in the 2 carbon stabilization scenarios is around 19 EJ, increasing to 24 EJ at the 75th percentile, and to 35 EJ in the highest scenario. To achieve this contribution requires hydro to deliver around 11% of global electricity supply in the medium case, or 14% at the 75th percentile.

The figure 5.30 represents the potential deployment scenarios of hydropower up to 2050 (high and low development scenarios). The graph is adapted from several studies {IEA, 2008; IEA, 2009 128; EREC, 2008}. Assuming low cost trend scenarios (see section 5.8) the realistic sustainable potential (approximately 9000 TWh/year) is reached in 2050. With econometrical changing assumptions, hydro deployment could even be higher and exceed 10000TWh a year.

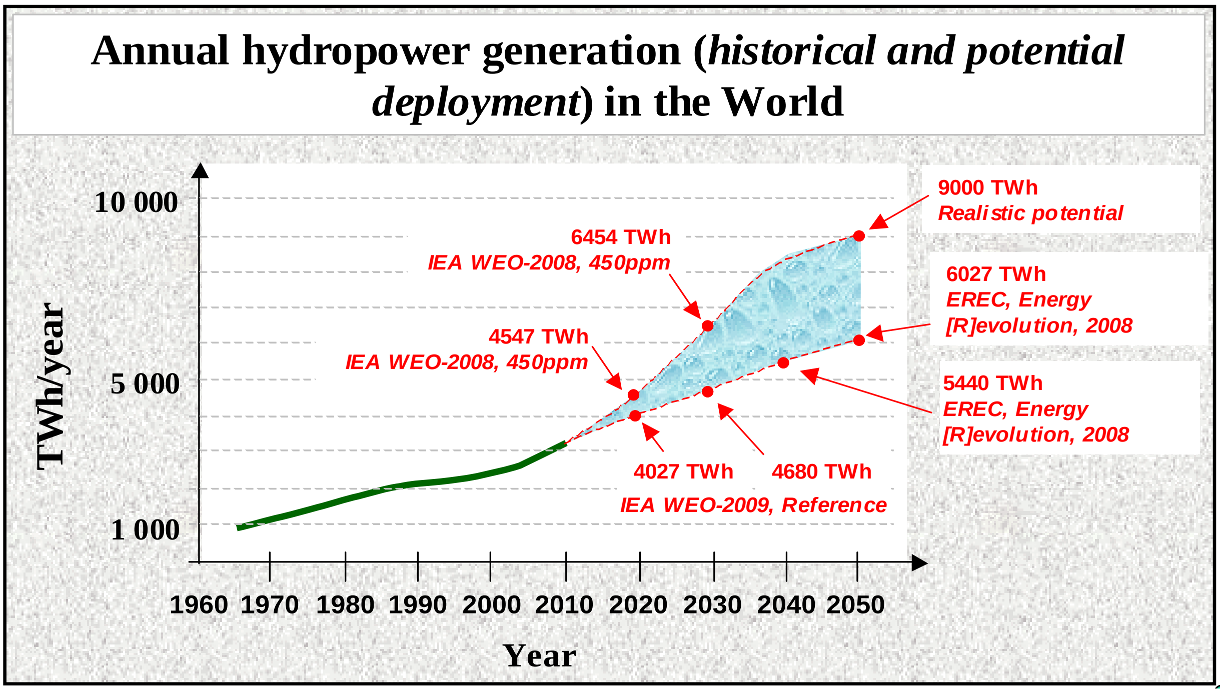

Figure 5.30: Hydropower development scenarios from 1960 to 2050 [TSU: source missing, caption not correct]

To achieve these levels there are no real technical and markets challenges, compared to other non mature RES technologies. Furthermore, a variety of possible challenges or opportunities to an aggressive growth of hydro may be added:

Resource Potential: First, even the highest estimates for long-term hydro production in Table 5.9 are within the global resource estimates presented in section 5.2, suggesting that technical resource potential is unlikely to be a barrier to hydro deployment. On a regional basis, however, higher deployment levels may begin to constrain the most economical resource supply (see section 10.3) in some regions.

Regional Deployment: Second, hydro would need to expand beyond its current status where most of the resource potential has been developed so far in Europe and North-America. The EIA reference-case forecast projects the majority of hydro deployment by 2030 to come majority (58%) from non-OECD Asia countries (e.g. 38% in China, and 8% in India), 22% from non-OECD Latin America (e.g., 17% Brazil), and 7% in both OECD Europe and OECD North-America (see Table 5.10). Regional collaboration can be enhanced in order to harmoniously combine power systems development with sound integrated water resources management, as it was assumed for example in Nile Basin Initiative or Great-Mekong Sub-Region development.

Table 5.10: Regional distribution of global hydro generation in 2006 and projection in 2030 (percentage of total worldwide hydro generation, average annual percent change from 2006 to 2030) (IEA, 2009).

U.S. EIA reference case for hydro generation deployment (EIA, 2009)		**2006 (History)**		**2030 (Projections)**		
		TWh	**% world hydro**	**TWh**	**% world hydro**	**2006-2030 average annual increase (%)**
OECD	OECD North America	671	22%	789	17%	0,7%
	United States	289	10%	301	6%	0,2%
	Canada	352	12%	447	9%	1,0%
	Mexico	30	1%	41	1%	1,3%
	OECD Europe	476	16%	604	13%	1,0%
	OECD Asia	127	4%	137	3%	0,3%
	Japan	85	3%	91	2%	0,3%
	South Korea	3	0%	4	0%	1,2%
	Australia / New Zealand	39	1%	42	1%	0,3%
	Total-OECD	**1 274**	**43%**	**1 530**	**32%**	**0,8%**
Non-OECD	Non-OECD Europe and Eurasia	300	10%	354	7%	0,7%
	Russia	174	6%	228	5%	1,1%
	Other	126	4%	127	3%	0,0%
	Non-OECD Asia	670	22%	1 693	35%	3,9%
	China	431	14%	1 098	23%	4,0%
	India	113	4%	262	5%	3,6%
	Other Non-OECD Asia	126	4%	333	7%	4,1%
	Middle-East	23	1%	44	1%	2,7%
	Africa	91	3%	126	3%	1,4%
	Central-and-South-America	640	21%	1 026	21%	2,0%
	Brazil	345	12%	647	14%	2,7%
	Other Central and South America	294	10%	379	8%	1,1%
	Total-Non-OECD	**1 723**	**57%**	**3 242**	**68%**	**2,7%**
Total-World		**2 997**	**100%**	**4 773**	**100%**	**2,0%**

Supply chain issues: Third, while efforts may be required to ensure an adequate supply of labour and materials during a long period (for instance more than 40 GW were installed in 2008, which is equivalent to the highest annual long-term IEA forecast scenario in its 450 ppm scenario WEO-2008), no fundamental long-term constraints to materials supply, labour availability, or manufacturing capacity are envisioned if policy frameworks for hydro are sufficiently attractive.

Technology and Economics: Fourth, hydro is a mature technology with very good economics compared to other RES, and cost competitive with other thermal units. Hydropower are in a broad range of types and size, and can meet both large centralised needs and small decentralised consumption.

Integration and Transmission: Fifth, hydro development occurs in synergy with other RES deployment. Indeed hydro with reservoirs and/or pumped storage power plants (PSPP) provide a storage capacity that can help transmission system operators (TSO) to operate their networks in a safe and flexible way, by providing back-up for intermittent variable RES (for instance wind, and solar PV). Hydro is useful for ancillary services and for balancing unstable transmission network, as hydro is the most responsive energy source for meeting peak demand (see Chapter 8). PSPP and storage hydropower can therefore ensure transmission, and also distribution, security and quality of services.

Social and Environmental Concerns: Finally, given concerns about social and environmental impacts of hydro projects, summarised in section 5.6, efforts to better understand the nature and magnitude of these impacts, together with efforts to mitigate any remaining concerns, will need to be pursued in concert with increasing hydro deployment. This work has been initiated by the World Commission on Dams (WCD, 2000) which has been endorsed and improved by International Hydropower Association (IHA, 2006) {IHA, 2003 #143;IHA, 2009 #144}which address these E&S issues. Concerns on fish migration, GHG emissions and water quality degradation in some tropical reservoirs, loss of biological diversity, and population displacement are perhaps the most prominent E&S impacts. However these impacts could be mitigated in most cases and even turned to positive impacts.

Overall, the evidence suggests that hydro high deployment levels in the next 20 years, remaining hydro as the leader of RES, are feasible. Even if hydro share in regards to the global electricity supply may decrease (from 16% to 10%-14% according to the scenarios) by 2050, hydro remains one of the most attractive RES within the context of global carbon mitigation scenarios. Furthermore this trend should continue given the world growing problem related to water resources (see section 5.10). Hydro can be vital for the economic and infrastructure development of poorer nations in terms of providing a steady supply of water and electricity. Besides providing a source of clean energy, hydropower dams are often essential for flood control, irrigation, drinking water supply, recreation, etc.

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 (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). Major IFIs are aware of the growing need for water storage (see Box 5.1, World Bank).

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 inter basin 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 – 2007d report (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 Multipurpose 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 multipurpose 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 multipurpose 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.

For instance China is constructing more than 90 000 MW of new hydro, and much of this development is designed for multipurpose utilization of water resources ((Zhu *et al.*, 2008). For the Three Gorges Project (22 400MW of installed capacity) the primary purpose of the project is flood control.

In Brazil, recommendations are provided to expand and sustain the generation of hydro, given the uncertainties of the current climatologic models when predicting future rainfall patterns in the Brazilian and in its trans-boundary drainage basins (Freitas, 2009; Freitas *et al.*, 2009).

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