Technology Roadmap

Hydropower

International Energy Agency

Ministério de Minas e Energia

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INTERNATIONAL ENERGY AGENCY

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Foreword

Current trends in energy supply and use are unsustainable – economically, environmentally and socially. Without decisive action, energy-related greenhouse gas (GHG) emissions could more than double by 2050, and increased oil demand will heighten concerns over the security of supplies. We can and must change the path we are now on; sustainable and low-carbon energy technologies will play a crucial role in the energy revolution required to make this change happen. To effectively reduce GHG emissions, energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse-gas emission goals. Every major country and sector of the economy must be involved and action needs to be taken now, in order to ensure that today's investment decisions do not burden us with suboptimal technologies in the long term.

There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To address these challenges, the International Energy Agency (IEA), at the request of the G8, is developing a series of roadmaps for some of the most important technologies needed to achieve a global energy-related CO_2 target in 2050 of 50% below current levels. Each roadmap develops a growth path for the covered technology from today to 2050, and identifies technology, financing, policy and public engagement milestones that need to be achieved to realise the technology's full potential.

Hydropower is the largest single renewable electricity source today, providing 16% of world electricity at competitive prices. It dominates the electricity mix in several countries, developed, emerging or developing. In many others it provides significant amounts of clean, renewable electricity. It also helps control water flows and availability. Its extreme flexibility is a strong asset for electric systems, and will be vital to accommodate and facilitate the growth of variable renewable energy technologies such as wind power and solar photovoltaics. It can foster social and economic progress, especially in developing countries. This roadmap considers that both annual hydropower capacities and generation should by 2050 roughly double from current levels.

Hydropower is a competitive energy source already today, but its further deployment still faces important regulatory, financial and public acceptance issues. This roadmap identifies those barriers and includes proposals to address them, including technology and managerial improvements enhancing the environmental performance of hydro.

Other IEA technology roadmaps have already included a special focus on the diffusion of clean energy technologies in countries beyond the IEA. As the bulk of the growth of hydropower will come from large-scale projects in emerging economies, the IEA benefited greatly from full-fledged cooperation from Brazil in elaborating and publishing this roadmap. Brazil, a leader in hydropower, shared its vast experience and knowledge. We are both confident that this novel and fruitful co-operation will broaden as we continue to seek solutions to the world's energy challenges.

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Key findings

- Hydroelectricity presents several advantages over most other sources of electrical power, including a high level of reliability, proven technology, high efficiency, very low operating and maintenance costs, flexibility and large storage capacity.
- Hydropower is the major renewable electricity generation technology worldwide and will remain so for a long time. Since 2005, new capacity additions in hydropower have generated more electricity than all other renewables combined.
- The potential for additional hydropower remains considerable, especially in Africa, Asia and Latin America. This roadmap foresees, by 2050, a doubling of global capacity up to almost 2 000 GW and of global electricity generation over 7 000 TWh. Pumped storage hydropower capacities would be multiplied by a factor of 3 to 5.
- Most of the growth in hydroelectricity generation will come from large projects in emerging economies and developing countries. In these countries, large and small hydropower projects can improve access to modern energy services and alleviate poverty, and foster social and economic development, especially for local communities. In industrialised countries, upgrading or redevelopment of existing plants can deliver additional benefits.
- Hydropower reservoirs can also regulate water flows for freshwater supply, flood control, irrigation, navigation services and recreation. Regulation of water flow may be important to climate change adaptation.
- Both reservoir and pumped storage hydropower are flexible sources of electricity that can help system operators handle the variability of other renewable energy such as wind power and photovoltaic electricity.
- In order to achieve its considerable potential for increasing energy security while reducing reliance on electricity from fossil fuels, hydropower must overcome barriers relative to policy, environment, public acceptance, market design and financial challenges.
- Large or small, associated with a reservoir or run-of-river, hydropower projects must be designed and operated to mitigate or compensate impacts on the environment and local populations. The hydropower industry has developed a variety of tools, guidelines and protocols to help developers and operators address the environmental and social issues in a satisfactory manner.
- New turbines and design make modern hydropower plants more sustainable and environmentally friendly; better management helps avoid damage to downstream ecosystems.
- Hydropower projects require very substantial up-front investment, which can range up to tens of billion USD. Although hydropower is the least-cost renewable electricity technology and is usually competitive with all alternatives, financing remains a key issue. This roadmap calls for innovative financing schemes and market design reforms to ensure adequate long-term revenue flows and alleviate risks for investors.

Key actions in the next ten years

Concerted action by all stakeholders is critical to realise the vision laid out in this roadmap. In order to stimulate investment on the scale necessary to achieve the aimed-for levels of sustainable hydropower, governments must take the lead in creating a favourable climate for industry investment. Actions necessary to achieve these targets relate to the policy and market framework, sustainability and public acceptance, financial challenges and further technology development.

With respect to policy, governments should:

- Establish or update an inventory of hydropower potential, at river basin level where appropriate; include options for upgrading or redeveloping existing plants to increase performance; assess feasibility of adding hydropower units to dams originally developed for flood control, irrigation, navigation or drinking.
- Prepare hydropower development plans with targets; and track progress towards meeting these targets. Least-developed countries could receive appropriate support to this end.
- Develop and promote a policy framework and market design for appropriate and sustainable hydropower projects.

With respect to sustainability and public acceptance, governments and relevant stakeholders should:

- Ensure that developers and operators document the approach to sustainability that will be followed, such as environmental impact assessment reports and/or voluntary protocols.
- Disseminate information to public and stakeholders on hydropower's role in producing sustainable energy and contributing to targets for climate change reduction.
- Consider sustainability issues in the co-ordinated operation of hydropower plants at electrical-interconnected river-basin level to take advantage of hydrological complementarities.

With respect to financial challenges, governments and relevant stakeholders should:

- Include the financing of hydropower on governments' policy agendas and develop new public risk-mitigating financing instruments.
- Develop effective financial models to support large numbers of hydropower projects in developing regions.
- Provide guidance to determine the real value of hydropower and pumped storage, and mechanisms for remuneration.
- Establish economic tools to assess the non-energy contributions of multi-purpose hydropower developments.

With respect to technology development, governments and industry should:

- Expand, co-ordinate and disseminate results of technology development to improve operational performance and reduce costs of development.
- Ensure that the industry develops technologies at hydropower plants to better support the grid integration of large amounts of variable renewable energy.

Introduction

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of energy security, climate change and sustainable development. This challenge was acknowledged by the energy ministers from G8 countries, China, India and Korea, in their meeting in June 2008 in Aomori, Japan, where they declared the wish to have IEA prepare roadmaps to advance innovative energy technology:

> *We will establish an international initiative with the support of the IEA to develop roadmaps for innovative technologies and co-operate upon existing and new partnerships [....] Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognise and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies...*

To achieve this ambitious goal, the IEA is developing a series of roadmaps to advance the development and deployment of low-carbon energy technologies, under international guidance and in close consultation with industry. These technologies are evenly divided among demand side and supply side technologies.

This hydropower roadmap has been developed in collaboration with CEPEL, the Brazilian Electric Energy Research Center, representing the Brazilian Ministry of Mines and Energy. The strong rationale behind this co-operation is the fact that the bulk of the current and future development of hydropower will take place in emerging economies; Brazil has accumulated considerable experience in the development of sustainable hydropower, while carrying out deep reform of its power sector. This conjunction makes Brazil's experience invaluable for other countries – whether developing, emerging or already industrialised.

The overall aim of the technology roadmap series is to advance global development and uptake of key technologies to achieve a 50% reduction in CO_2 emissions by 2050 (over 2005 levels). The roadmaps will enable governments and their industry and financial partners to identify the steps needed and implement measures to accelerate required technology development and uptake.

Rationale for hydropower

Hydropower is a mature and cost-competitive renewable energy source. It plays an important role in today's electricity mix, contributing to more than 16% of electricity generation worldwide and about 85% of global renewable electricity. Furthermore, it helps stabilise fluctuations between demand and supply. This role will become even more important in the coming decades, as the shares of variable renewable electricity sources – primarily wind power and solar photovoltaic (PV) – will increase considerably.

The contribution of hydropower to decarbonising the energy mix is thus twofold: the primary benefit is its clean, renewable electricity. The secondary benefit is as an enabler to greater contribution of other renewables on the grid.

Hydropower development often contributes other benefits. The most important are water supply, flood and drought control, and irrigation; but navigation and recreational activities also have their place. These objectives can conflict at times, but are more often complementary. Providing such multiple outcomes from sustainable hydropower development is central to this roadmap.

Hydropower is too often overlooked in energy policies. Policy makers, especially in industrialised countries, tend to believe that the economic potential for hydropower plant was exhausted decades ago, and/or that hydropower plants are detrimental to the protection of the environment, or unsafe. The possible contribution of hydropower to help balance fluctuations in electricity supply from wind and solar PV is not always understood. However, economic conditions are changing fast, technologies are improving, and environmental, social and economic conditions of sustainability are better understood and more often taken into consideration. In general, the safety of dams is now very high, and there are substantial options to increase the capacity, efficiency and environmental performance of old plants – and many opportunities to build new ones, especially in emerging and developing economies.

Looking to the future, the most important drivers for hydropower development will continue to be:

- long and productive local generation capability and low life-cycle costs;
- proven reliability of electricity production, with few service interruptions;
- safe operation, with minimum risks to hydropower staff and the general public;
- environmental and socially sustainable development, providing climate change mitigation;
- flexible operations, energy services enhancing grid stability and enabling use of variable renewables;
- large-scale energy storage for seasonal load balancing;
- provision of many non-energy services such as flood control, water supply and irrigation, especially in the context of growing freshwater needs and adaptation to climate change;
- upgrades, redevelopments and improvements to existing hydropower plants;
- addition of hydropower facilities, where feasible, to existing dams originally built to provide flood control, irrigation, water supply and other non-energy purposes; and
- energy security with local generation.

Purpose, process and structure of this roadmap

This roadmap aims to identify the primary actions and tasks that must be undertaken to accelerate hydropower development and deployment globally. Hydropower is a mature energy technology; most technical improvements today aim to minimise its possible negative environmental impacts and maximise its environmental benefits, while maintaining very high efficiency and acceptable costs. Hydropower plants have low running costs and shield end-users against fossil fuel price volatility, but their potentially extended technical life carries heavy initial investment costs. Hence, financing is possibly the most critical issue; its solution rests in large part on policy framework and market design. Governments, whether in developing, emerging or mature economies, thus bear a critical responsibility in enabling the deployment of hydropower.

The IEA convened a first Hydropower Roadmap Workshop in Paris, France (26-27 May 2011) to initiate the work, with a broad agenda including environmental and financing issues. The Brazilian Electric Energy Research Center, CEPEL, hosted a second workshop in Rio de Janeiro, Brazil (10-11 October 2011), with a focus on the Americas and Asia. The IEA convened a third workshop in Paris (9 May 2012) to discuss the shared vision for hydropower deployment and key actions and milestones. Finally, a short wrap-up session was organised in Washington, DC (30 May 2012) in the margins of the meetings of the IEA Hydropower programme.

This roadmap is organised in six major sections. It starts with the status of hydropower today, revealing its diversity.[1] It continues with a vision for future deployment of hydropower, given its still undeveloped potential, detailing regional scales; this section includes considerations on the broader context of renewable deployment and the role of hydropower as an enabler for variable renewables. The following section considers the dimensions of sustainability, detailing environmental issues, socio-economic and public acceptance issues, sustainable approaches to deployment, and the energy-water nexus. The fifth section reviews the economics of hydropower – costs, support mechanisms and financial challenges. The roadmap then looks at continuing and future technology improvements, before addressing the policy framework, listing actions and milestones. It concludes by listing near-term actions for stakeholders.

1. Note, however, that this roadmap does not include information on tidal and wave plants.

Hydropower today

Overview

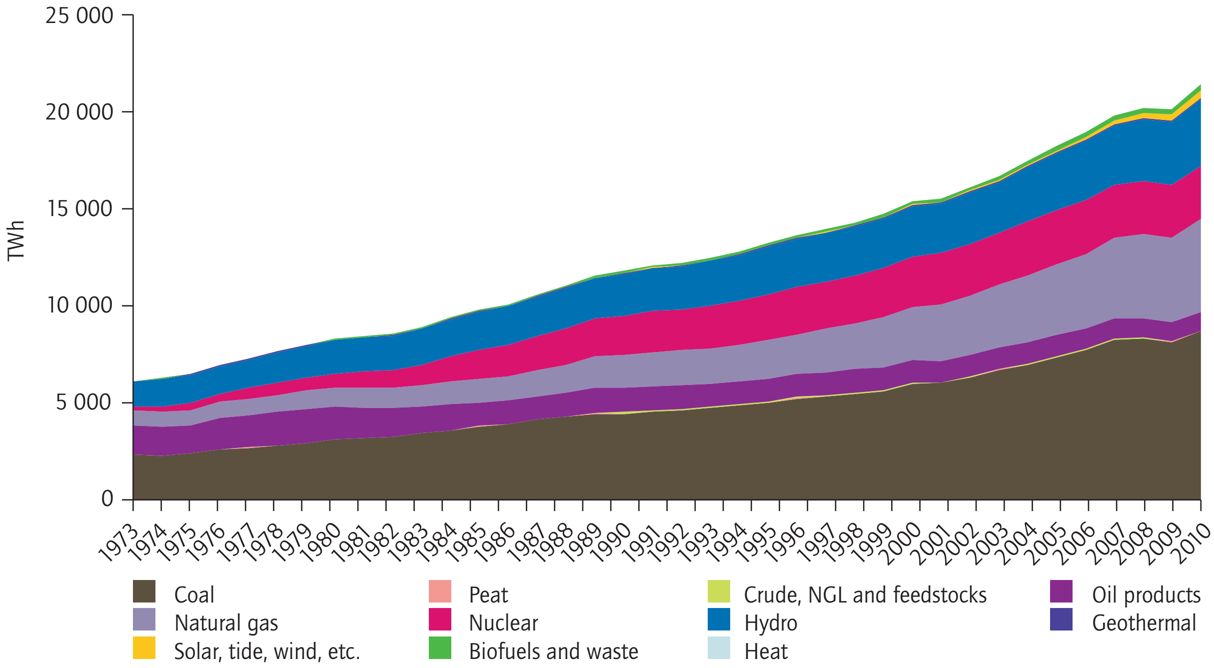
The mechanical power of falling water has been used for millennia in many parts of the world. Its coupling with the electrical generator in the late 19th century gave birth to hydro-electricity, the main source of electricity at the dawn of the 20th century, *e.g.* generating 40% of the power produced in the United States by 1920. With many towns, cities and industries located near rivers, hydropower was able to supply electricity from plants close to the load centres. Hydropower, nicknamed "white coal", was then very popular.

Since these early developments, hydropower has developed as a safe, reliable and inexpensive source of power and energy services. The knowledge of how to responsibly manage environmental and social impacts has considerably improved in the last decades, reaching a generally high level. Hydropower provides the largest share of renewable electricity worldwide and still has a large potential for future development. In addition, the fast response capabilities of large reservoir and pumped storage plants provide critical energy services to networks, helping to match fluctuations in electricity demand and supply from less flexible electricity sources. As hydropower plants have become larger, their associated dams have developed additional purposes such as water supply, flood control, irrigation, navigation and fisheries. Conversely, hydroelectricity generators have been added to dams initially built for flood control, irrigation and/or navigation purposes.

Hydropower is a fully mature technology in use in 159 countries. It provides 16.3% of the world's electricity (about 3 500 TWh in 2010), more than nuclear power (12.8%),[2] much more than wind, solar, geothermal and other sources combined (3.6%), but much less than fossil fuel plants (67.2%) (IEA, 2012a). In OECD countries, hydropower's contribution is 13% (about 1 400 TWh in 2008). This is smaller than in non-OECD countries (19.8%, about 2100 TWh in 2008), where it has increased by an annual average 4.8% growth rate since 1973 (Figure 1).

2. This is not readily apparent from most published primary energy statistics, as their conventions apply different values to the primary energies of nuclear and hydropower.

Figure 1: Global electricity generation by fuel, 1973-2010



Source: Unless otherwise indicated, material in all figures, tables and boxes derives from IEA data and analysis.

Four countries (China, Brazil, Canada and the United States) together produce half the world hydropower generation; ten countries produce 70% (Table 1).

More than 35 countries obtained more than half of their total electricity from hydropower in 2009 (Table 2).

Table 1: Top ten hydropower producers in 2010

Country	*Hydro electricity (TWh)*	*Share of electricity generation (%)*
China	694	14.8
Brazil	403	80.2
Canada	376	62.0
United States	328	7.6
Russia	165	15.7
India	132	13.1
Norway	122	95.3
Japan	85	7.8
Venezuela	84	68
Sweden	67	42.2

Note: These numbers do not include electricity imports such as those from the Itaipu hydropower plant side of Paraguay to Brazil, which represent almost half of this hydropower plant generation (36 TWh).

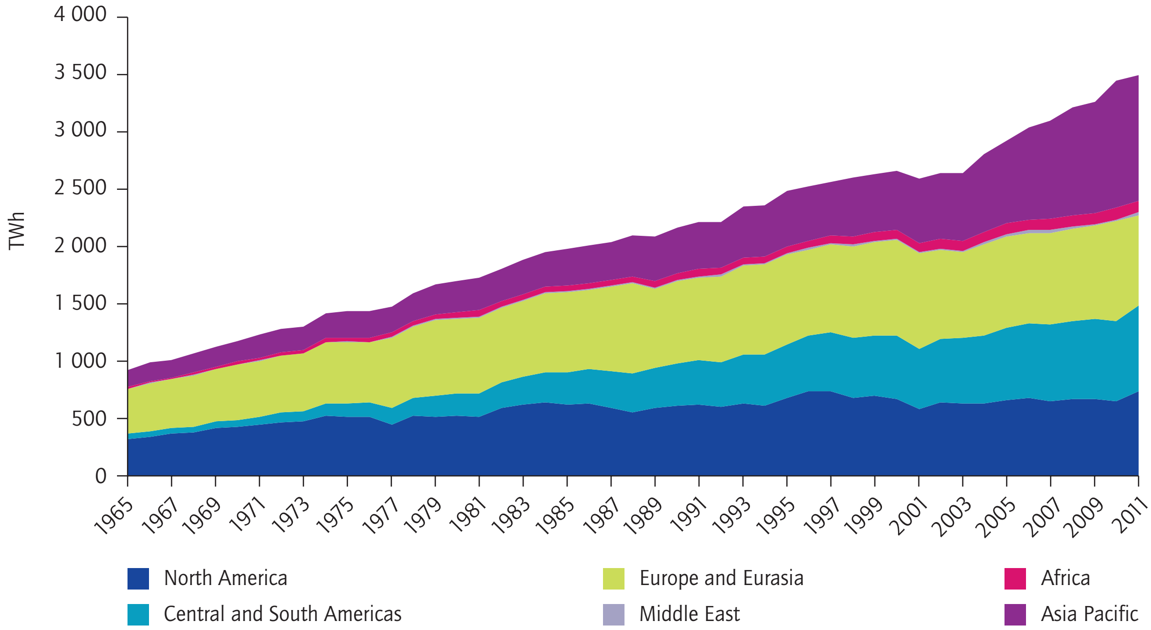
Table 2: Countries with more than half their electricity generation from hydropower in 2010

Share of hydropower	*Countries*	*Hydropower Generation (TWh)*
≈100%	Albania, DR of Congo, Mozambique, Nepal, **Paraguay**, Tajikistan, Zambia	**54**
>90%	**Norway**	**126**
>80%	**Brazil**, Ethiopia, Georgia, Kyrgyzstan, Namibia	**403**
>70%	Angola, Columbia, Costa Rica, Ghana, Myanmar, **Venezuela**	**77**
>60%	**Austria**, Cameroon, **Canada**, Congo, Iceland, Latvia, Peru, Tanzania, Togo	**38; 351**
>50%	Croatia, Ecuador, Gabon, DPR of Korea, **New Zealand**, Switzerland, Uruguay, Zimbabwe	**25; 36**

Note: Countries in bold are those where hydropower generation exceeded 20 TWh in 2009 and is indicated in the last column on the right.

Hydropower is not considered variable in the same sense as wind power or solar PV. This is in part due to the control over the source through its storage capabilities and the greater predictability (over wind power) of its generation (even for run-of-river plants). Hydropower is, however, variable over longer time scales, as it depends on precipitation and water run-off. The long-term output trend reflects the growth of hydropower capacities worldwide, with an increase of 52% from 1990 to 2009 (Figure 2), with a particularly rapid growth in China (Brown *et al*., 2011). A slowdown between the late 1990s and the early 2000s resulted from escalating local and international controversies over large dams, among other factors. This led to the establishment of the World Commission on Dams (WCD) and the publication of a major report in November 2000, *Dams and Development: A new framework for Decision-making* (WCD, 2000). In 2003, the World Bank approved its *Water Resources Sector Strategy*, which supports renewable energy and renewable efficiency (World Bank, 2003). In 2009, the World Bank highlighted the importance of multi-purpose infrastructure as a driver for future hydropower development (World Bank, 2009).

Figure 2: Hydroelectricity generation, 1965-2011



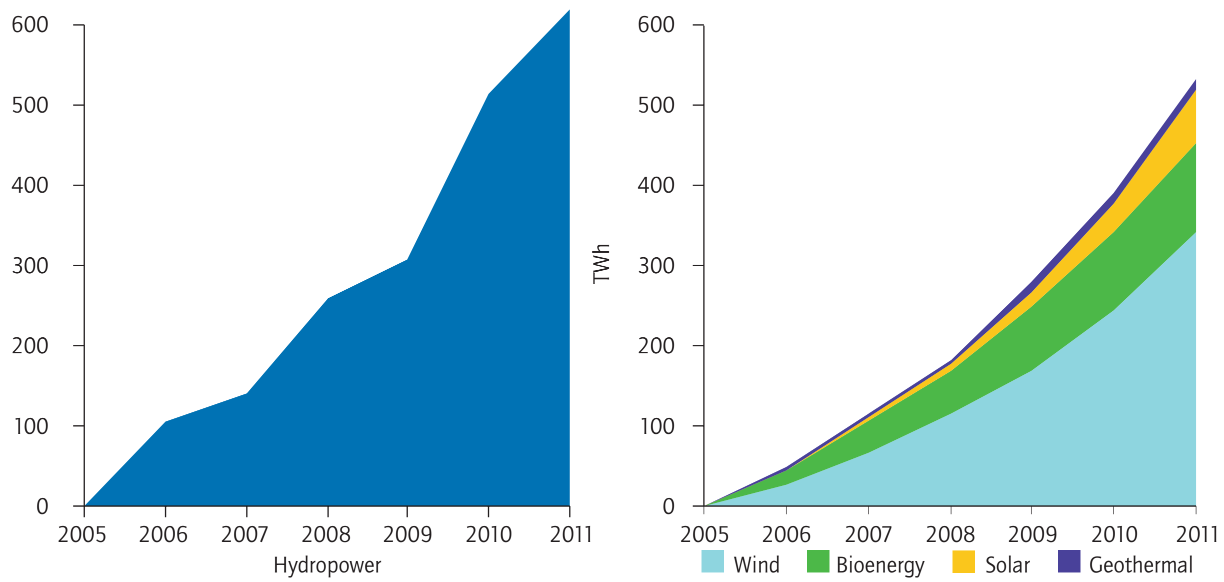
Sources: BP, 2012 and IEA analysis.

Hydropower capacity is on the rise, reaching 1 000 GW worldwide at the end of 2010. Its average annual growth rate of about 2.5% looks small, especially when compared to growth rates of wind and solar – but this ignores its large existing base. In the last decade, electricity generation from additional hydro capacities has kept pace with generation from all other renewables together (Figure 3).

Diversity of hydropower

Hydropower plants are very diverse in terms of size and type of plant, size and type of generating unit, the height of the water fall ("head"), their functions (electricity generation, capacity or multi-purpose) and sizes. They are extremely site specific and tailor-made to local conditions. This roadmap primarily classifies hydropower plants (HPP) in three functional categories: run-of-river (RoR), reservoir (or storage) HPP, and pumped storage plants (PSP). RoR and reservoir HPP can be combined in cascading river systems and PSP can utilise the water storage of one or several reservoir HPPs.

Figure 3: Electricity generation from recent additions to hydropower (left) and other renewables (right)



Source: IEA, 2012b.

Run-of-river

An RoR hydropower plant harnesses energy for electricity production mainly from the available flow of the river. These plants may include short-term storage or "pondage", allowing for some hourly or daily flexibility in adapting to the load demand profile, but the generation profile is mostly driven by natural river flow conditions or releases from any upstream reservoir HPP. In the absence of such upstream reservoir HPP, generation depends on precipitation and runoff, and normally has substantial daily, monthly, seasonal and yearly variations.

Reservoir

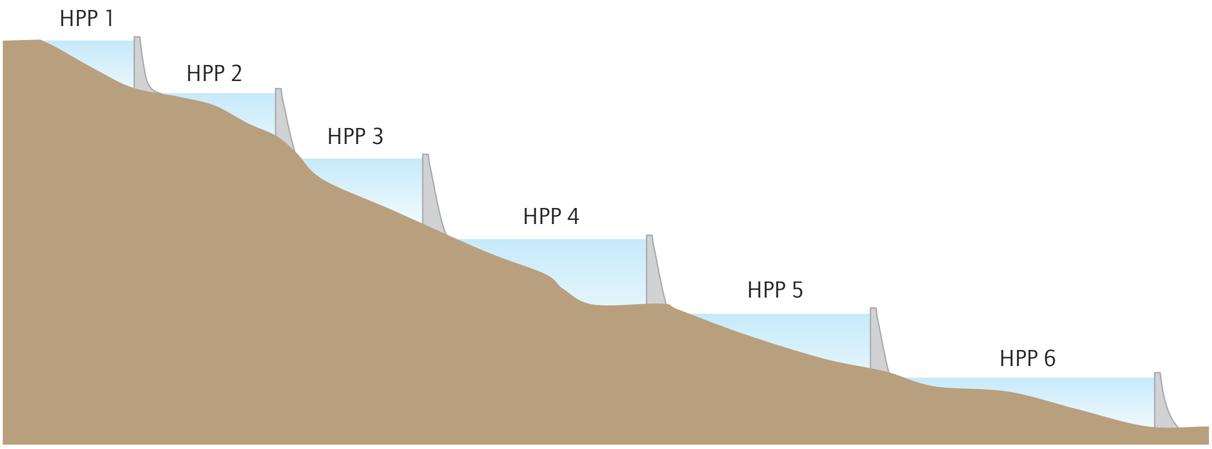
Storing water in a reservoir provides the flexibility to generate electricity on demand, and reduces dependence on the variability of inflows. Very large reservoirs can retain months or even years of average inflows and can also provide flood protection and irrigation services. In general, most reservoir schemes serve various purposes. The hydro plant design and provision of these services is very much dependent on the environment and social needs of the region and local project conditions. Most reservoirs are artificially created by building a dam to control the natural river flow. When local conditions allow, natural lakes can also function as reservoirs.

Reservoir HPP are characterised by their size, electrical capacity and generation potential. If the capacity is small compared to the generation potential and if the reservoir size allows, the HPP might be used for base load, round the clock and in all seasons. Conversely, larger turbines would more rapidly exhaust the potential; generation in this case would preferably take place during hours of peak demand.

Cascading systems

The energy output of a RoR HPP could be regulated by an upstream reservoir HPP, as in cascading hydropower schemes (Figure 4). A large reservoir in the upper catchment generally regulates outflows for several RoR or smaller reservoir plants downstream. This likely increases the yearly energy potential of downstream sites, and enhances the value of the upper reservoir's storage function. For example, on the river Durance in France, 15 cascading HPPs produce annually 7 TWh, and have the capability to add 2 GW to the electrical network within 10 minutes. To optimise total output, some countries (*e.g.* Norway), in which individual HPPs may be owned by different firms, organise the cascade in a "regulator association".

Figure 4: Cascading hydropower plants

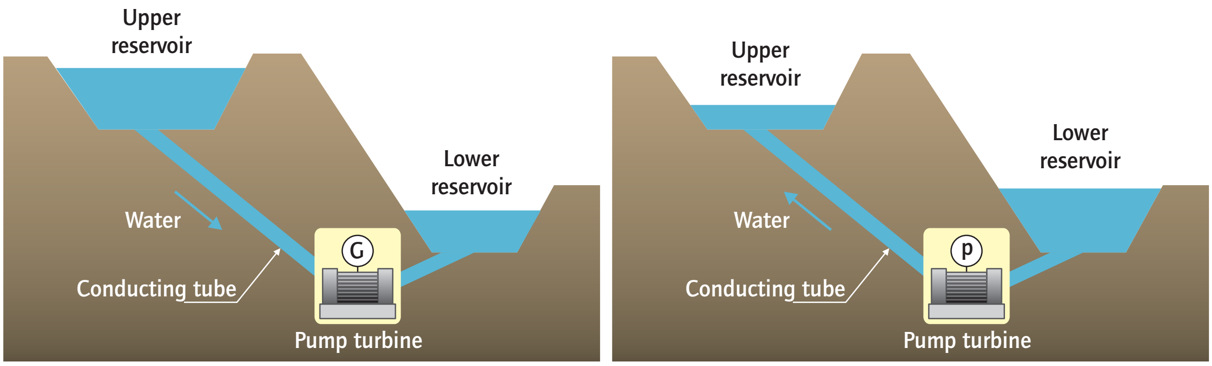


Source: CEPEL.

Pumped storage hydropower

In pumped storage plants or projects (PSPs), water is pumped from a lower reservoir into an upper reservoir when electricity supply exceeds demand or can be generated at low cost. When demand exceeds instantaneous electricity generation and electricity has a high value, water is released to flow back from the upper reservoir through turbines to generate electricity (Figure 5). Both reservoir HPPs and PSPs store potential energy as elevated water for generating on demand. The difference is that PSPs take energy from the grid to lift the water up, then return most of it later (round-trip efficiency being 70% to 85%), so PSP is a net consumer of electricity but provides for effective electricity storage. Pumped storage currently represents 99% of on-grid electricity storage (EPRI, 2010).

Figure 5: Pumped storage plant



Source: Inage, 2009.

Most PSPs are "open-loop" systems developed from an existing HPP system by addition of either an upper or a lower reservoir. They are usually "off-stream". The off-stream configuration consists of a lower reservoir on a stream, river or other water source, and a reservoir located off-stream usually at a higher elevation. (It is possible to have the off-stream reservoir at a lower elevation such as an abandoned mine or underground cavern). Another type is the "pump-back" project using two reservoirs in series: a conventional hydro project with a pumped storage cycle imposed on the normal hydropower operations. Pumping from the downstream reservoir during low-load periods makes additional water available to use for generation at high demand periods. Finally, closed-loop systems are completely independent from existing water streams – both reservoirs are off-stream.

IEA analysis shows that existing installed turbine capacity in PSP projects worldwide neared 140 GW at the end of 2011, up from 98 GW in 2005. Leading countries/regions include the European Union (45 GW), Japan (30 GW), China (24 GW), and the United States (20 GW). PSP, like HPP, cannot be characterised only by electrical capacities. In Spain, the 17 PSPs allow storage of 1.5 TWh of electricity in an "ideal" pumping cycle starting with empty upper reservoirs and full lower reservoirs, and finishing with either full upper or empty lower reservoirs. In the alpine countries, by contrast, 16 PSPs store only 369 GWh in Switzerland, 9 PSPs store 184 GWh in France, and 15 PSPs store 125 GWh in Austria (EURELECTRIC, 2011).

The yearly potential of PSPs depends also on the number of cycles they perform. When variability arises from both demand and generation (usually as a consequence of increasing penetration of variable renewables), the cycling may accelerate, *i.e.* PSP may shift between pump and turbine modes several times per day, so increasing the yearly energy finally stored and returned to the grid.

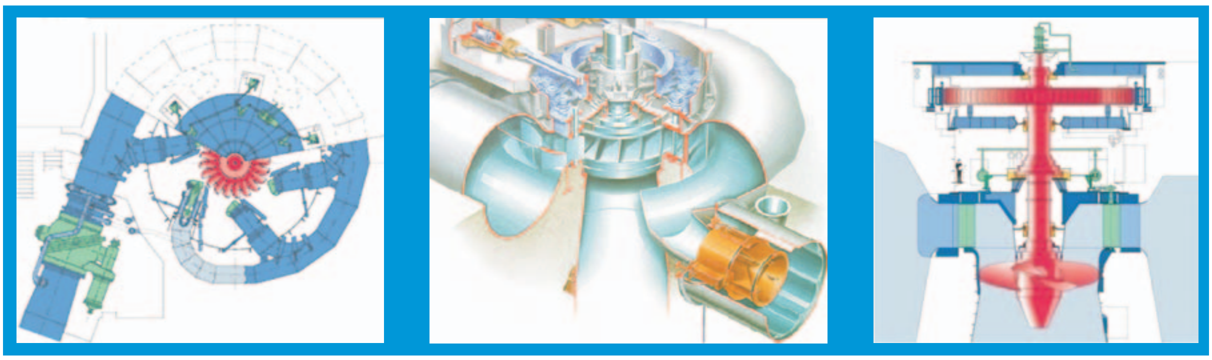
Classification by hydraulic head or powerplant size

A classification by hydraulic head refers to the difference between the upstream and the downstream water levels. The classifications of "high head" (say, above 300 m) and "low head" (say, less than 30 m) technologies vary widely from country to country, and there are no generally accepted scales. Head determines the water pressure on the turbines. Together, head and discharge are the most important parameters for deciding the type of hydraulic turbine to be used.

For high heads and small flows, Pelton turbines are used, in which water passes through nozzles and strikes spoon-shaped buckets arranged on the periphery of a wheel (Figure 6, left). A less efficient variant is the crossflow turbine. These are action turbines, working only from the kinetic energy of the flow.

Francis turbines are the most common type, as they accommodate a wide range of heads (20 m to 700 m), small to very large flows, a broad rate capacity and excellent hydraulic efficiency. Guide vanes direct the water tangentially to the turbine wheel; the water enters the wheel and exits it in the middle (Figure 6, centre). The guide vanes are adjustable to optimise output and efficiency over the variations in head and flow conditions.

Figure 6: Pelton, Francis and Kaplan turbines



Sources: Voith Siemens; Andritz

For low heads and large flows, Kaplan turbines, a propeller-type water turbine with adjustable blades, dominate (Figure 6, right). Kaplan and Francis turbines, like other propeller-type turbines, capture the kinetic energy and the pressure difference of the fluid between entrance and exit of the turbine.

Classification according to installed capacity (in megawatts or MW) has led to concepts such as “small hydro” and “large hydro”, but there is no worldwide consensus on size categories. Different countries or groups of countries define small hydro differently (from below 1.5 MW in Sweden to below 50 MW in China), so small-scale hydro spans a very wide range of plants (Table 3). This broad spectrum relates to countries' local energy and resource management needs. Some have even used terms such as “mini-hydro”, “micro-hydro” and “pico-hydro”, but again with no widely accepted definitions. Indeed HPP capacities range from several watts (W) for the smallest individual installations, to tens of gigawatts (GW) or billions watts for the largest. HPP of capacity lower than 10 MW are estimated to represent about 10% of the global HPP capacity. While most small-scale HPP seem to be RoR, there are also quite large RoR HPP.

Table 3: Definitions of small-scale hydro in different count

Country	Small-scale hydro as defined by capacity (MW)	Reference
Brazil	<30	Brazil Gvt Law 9648 May 27, 1998
Canada	<50	Natural Resources Canada, 2009
China	<50	Jinghe (2005), Wang (2010)
European Union	<20	Directive 2004/101/EC (“Linking Directive”)
India	<25	Ministry of New and Renewable Energy, 2010
Norway	<10	Norwegian Ministry of Petroleum and Energy 2008
Sweden	<1.5	European Small Hydro Association
United States	5-100	US National Hydropower Association

Energy services

Reservoir HPP and PSP can provide electricity grids with a full range of energy services, including:

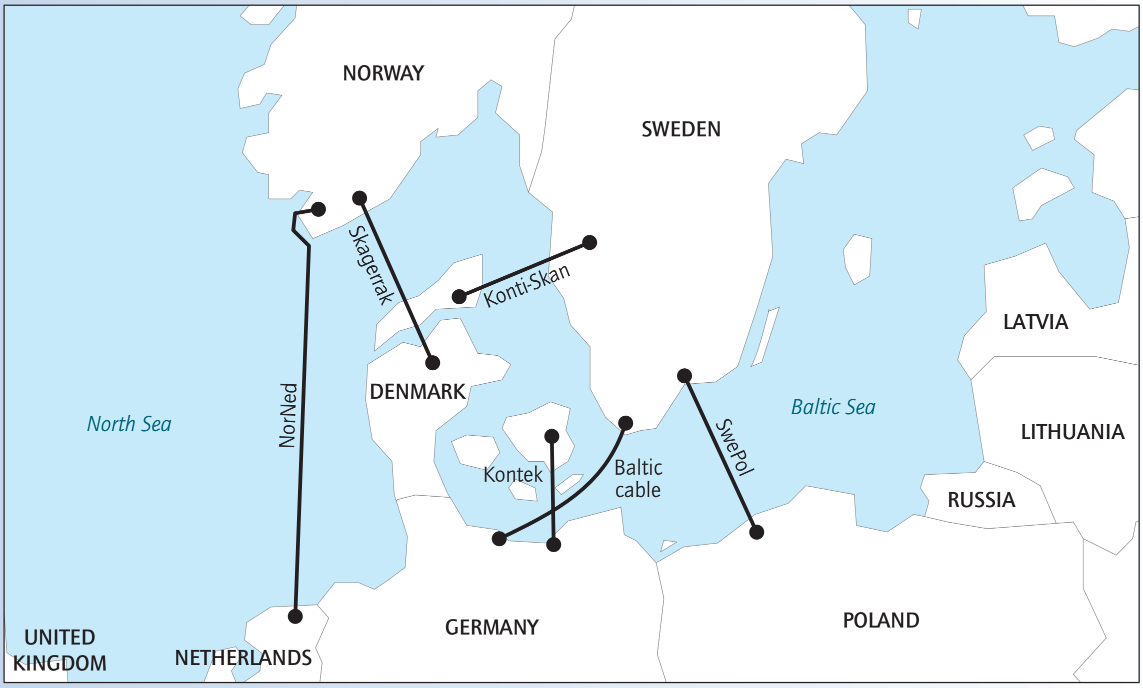
- **Back-up and reserve with quick start and shutdown capabilities.** Hydropower plants can enter load (or stop) within a few minutes at any time (secondary control), while the most responsive combustion turbines require half an hour, and steam turbines several hours.
- **Spinning reserve.** Hydropower can provide spinning reserve, or additional power supply that can be made available in seconds, in case of unexpected load changes in the grid (primary control), when operating below maximum power.
- **Black start capability.** A black start is the process of restoring a power station to operation without relying on the external electric power transmission network. Hydropower plants are usually designated as the black start source to restore an entire electricity network in case of complete outage. This avoids the need for over-investment in conventional power plants, as for large fossil-fuel plants a black start would require a cascade of smaller capacities.
- **Regulation and frequency response.** Hydropower helps to maintain the power frequency by continuous modulation of active power, and to meet moment-to-moment fluctuations in power requirements. It offers rapid ramp rates and usually very large ramp ranges, making it very efficient to follow steep load variations.

Box 1: Hydro backing wind power: the Denmark-Norway connection

Denmark is the country showing the highest share (24%) of wind power in its electricity generation. It is a flat land with no opportunities for hydropower or PSP. However, it is close to Sweden and Norway, which have considerable hydropower potential. Over decades, several high-voltage direct-current (HVDC) connecting cables have been built between these countries, as well as with Germany, the Netherlands and Poland (Figure 7).

The 240-km long Skagerrak 1-3 lines between Denmark and Norway, including 127-km long underwater cables, have an overall capacity of 1 050 MW. Starting in the 1970s, they were designed to avoid the building of a thermal plant in Norway, which would have been needed only during very dry years, while giving Denmark more peaking capacity. At present, a new cable, Skagerrak 4, is felt "necessary to integrate more wind power into the Danish power system and to enhance the efficiency and competitiveness of the electricity market" (Energinet, 2012). It will add about 700 MW of exchange capacity by 2014.

Figure 7: The Scandinavia - Northern Europe interconnections



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

- **Reactive power compensation and voltage support.** Hydropower can control reactive power, thus ensuring that power flows from generation to load. It also helps maintain voltage through injecting or absorbing reactive power by means of synchronous or static compensation.

Run-of-river HPP, when not downstream of reservoir HPP, does not provide back-up and reserve, but is nevertheless able to provide, at least in part, the other ancillary services mentioned here. As variable (though reasonably predictable) and non-manageable renewable energy, RoR HPP is usually considered part of the base load in electricity grid, while reservoir HPP play a significantly larger role for peak, shoulder and base loads. PSP are mostly used as peak load generating capacities.

The enabling role of hydropower

The flexibility of HPP, especially reservoir plants, and its many contributions to ancillary services determine its excellent ability to balance the variability of some other renewables (Box 1). Recent studies have thoroughly examined these complementary factors. IEA Wind (2011) shows that addressing the balancing impacts of wind integration needs to be done in the context of the entire system, with all of its load and generation resources, and not in isolation (*i.e.* not one wind power plant balanced by one hydro plant to produce a flat output). Depending on the relative capacities of the wind and hydropower facilities, wind integration may necessitate changes in the way hydropower facilities operate to provide balancing, reserves or energy storage. These changes may affect operation, maintenance, revenue, water storage and the ability of the hydro facility to meet its primary purposes. On the other hand, integration with wind could create new economic opportunities for the hydro system.

Non-power constraints on the hydropower system, such as irrigation water deliveries, environmental regulation (*e.g.* fish passage), recreation, and flood control tend to reduce the ability of hydropower to integrate variable renewables. Limitations on flow variability, currently in place in some jurisdictions, are a very important constraint, particularly as they may affect fluctuations in tailwater (downstream) levels.

Vision for hydropower deployment

This section first considers the technical potential for hydropower, then short-term deployment perspectives, and, based on IEA modelling, deployment perspectives till 2050. These are then detailed for most regions of the world. After elaborating on the broader context of renewable energy deployment, the text considers the specifics of pump-storage hydropower, as well as its deployment perspectives. Finally, the contribution of hydropower deployment to CO_2 emission reductions till 2050 is assessed.

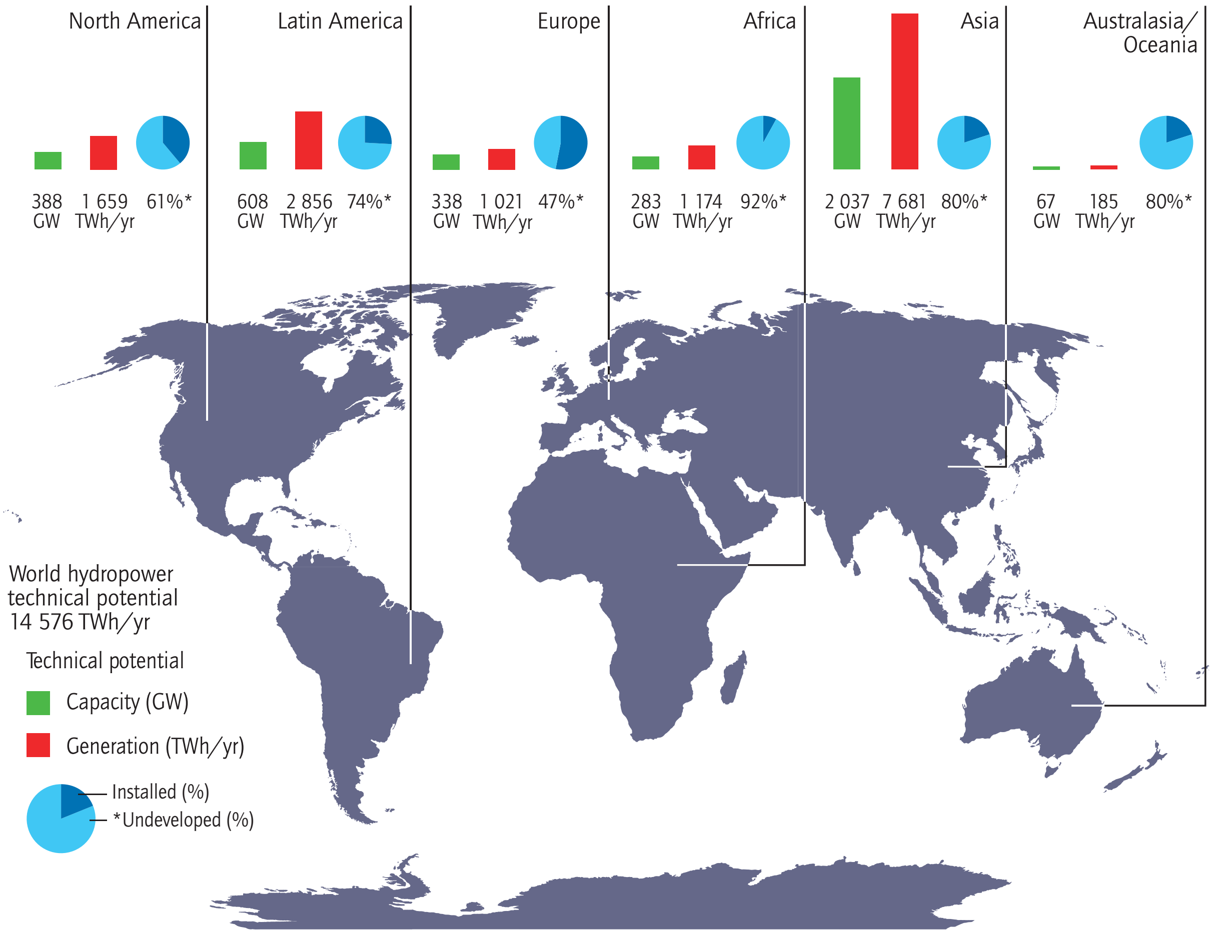
Technical potential

The technical potential for hydropower is usually estimated at around 15 000 TWh/yr, or about 35% of a theoretical potential derived from the total annual runoff of precipitation (*e.g.* IJHD 2010). This technical potential would require a global capacity of 3 750 GW at 4 000 full load hours. The percentage of undeveloped technical potential is highest in Africa (92%), followed by Asia (80%), Australia/Oceania (80%) and Latin America (74%) (Figure 8). Even in the most industrialised parts of the world, the undeveloped potential remains significant, at 61% in North America and 47% in Europe.

Short-term deployment

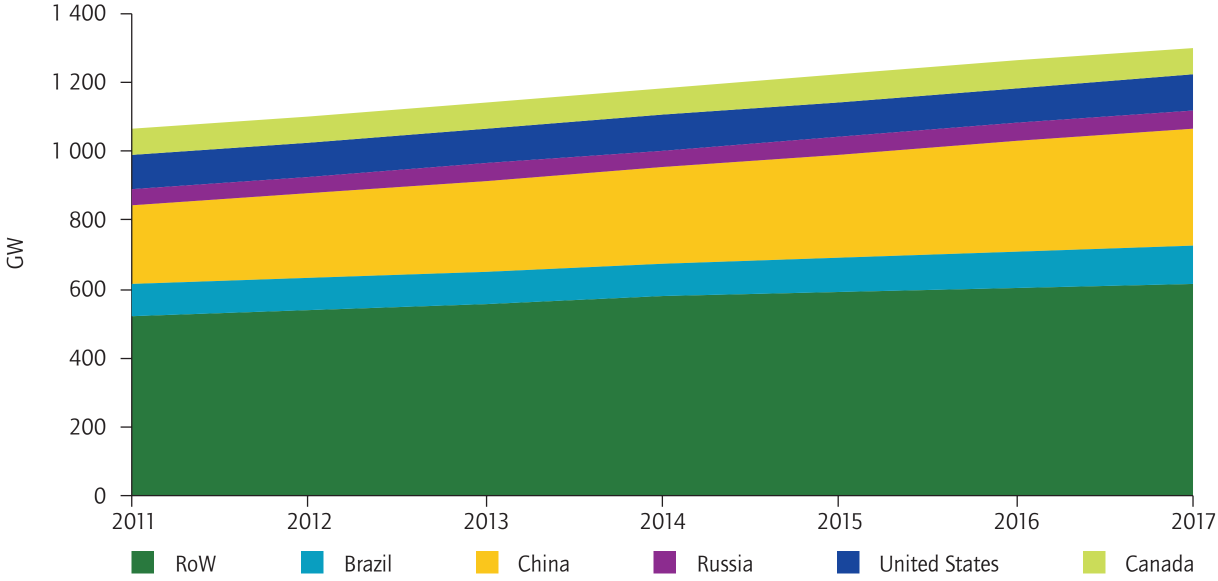
Global installed hydropower capacities have been growing in recent years at an average of 24.2 GW per year, and reached 1 067 GW at the end of 2011 (including pumped storage capacities). Total capacity is expected to reach 1 300 GW in 2017 (IEA, 2012b) (Figure 9). Given the long lead times of HPP development, these figures represent capacities in construction virtually certain to come on line.

Figure 8: Regional hydropower technical potential and percentage of undeveloped technical potential (2009)



Source: IPCC, 2011, based on IJHD, 2010.

Figure 9: Expected mid-term evolution of hydropower installed capacity (GW)

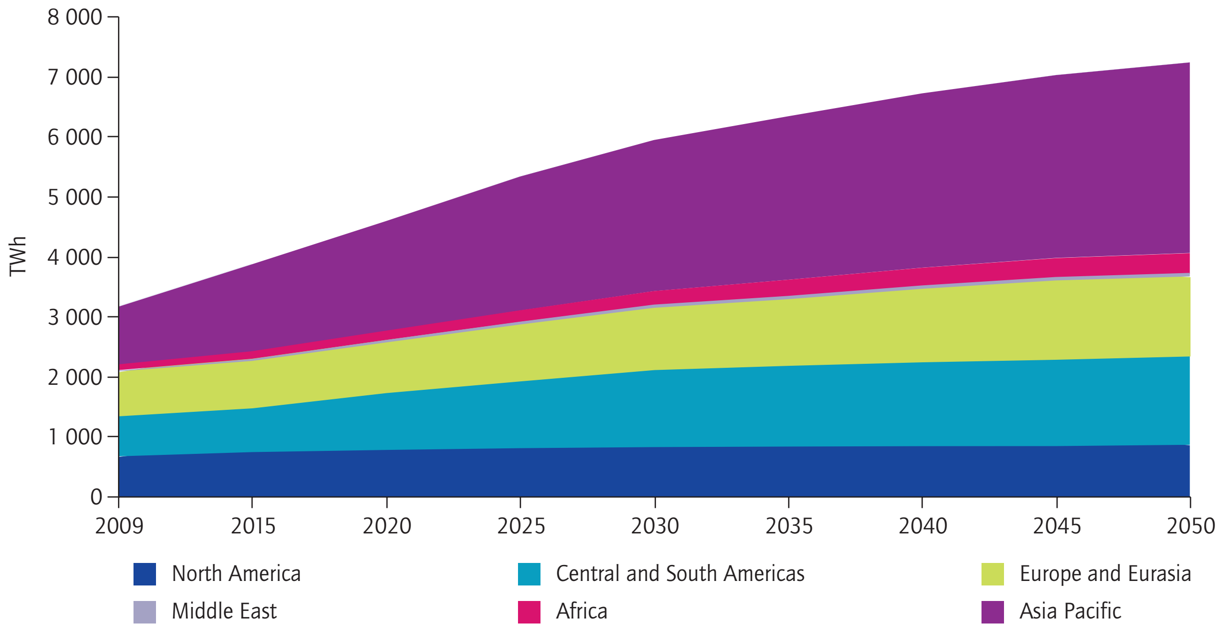


Source: IEA, 2012b.

Long-term deployment

The vision of the long-term deployment of hydropower in this roadmap is based on the 2°C Scenario of the IEA *Energy Technology Perspectives 2012* (ETP 2DS). This describes how energy technologies across all energy sectors may collectively achieve the goal of reducing annual CO_2 emissions to half that of 2009 (IEA, 2012c). The ETP model uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources.

Figure 10: Hydroelectricity generation till 2050 in the Hydropower Roadmap vision (TWh)

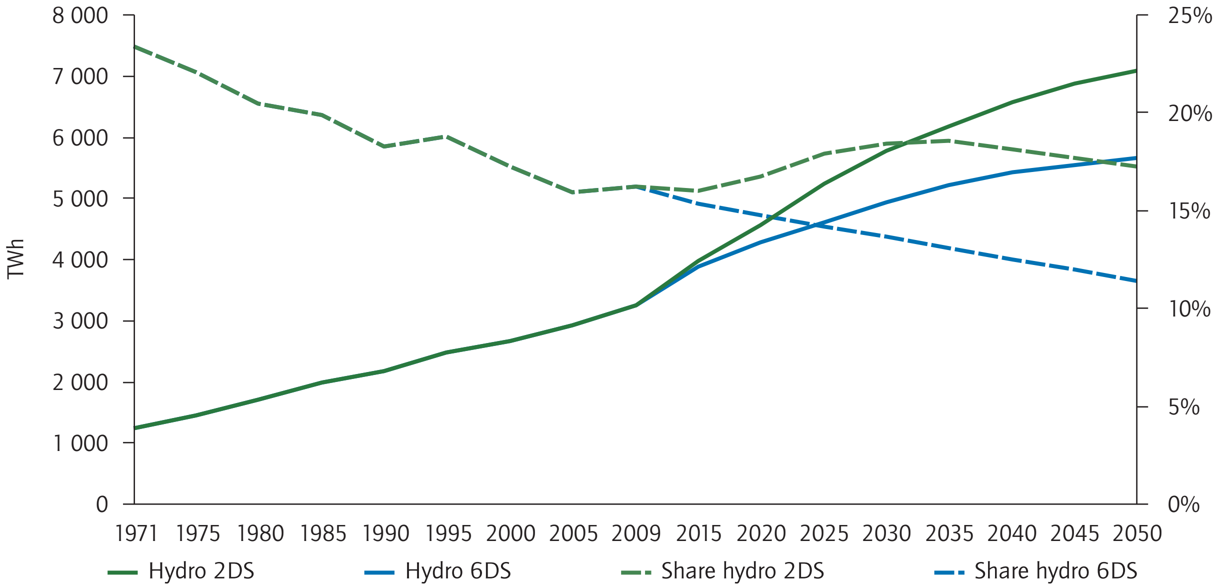


Sources: IEA, 2012c and MME data.

The 2DS estimates a global installed hydropower capacity by 2050 of 1 947 GW, nearly twice the current level (IEA, 2012c). Generation of hydro-electricity would near 7 100 TWh, a doubling of current generation. Hydro"s share of total electricity generation would be roughly constant. The growth of hydropower generation is largely focused in emerging economies (Figure 10). In this roadmap, numbers for Brazil have been aligned on the country's own forecasts.

In the baseline or 6°C Scenario (6DS), despite an increase in absolute figures to over 5 700 TWh, hydroelectricity generation would continue to decline as a share of total electricity generation, following a long historical trend. By contrast, in the 2DS the share of hydropower would rebound before declining again after 2035, as a result of more rapid growth of this clean energy resource and a slower growth of the total generation due to increased energy efficiency (Figure 11).

Figure 11: Historical hydroelectricity generation and projections in ETP 6DS and 2DS, in TWh and shares of total electricity generation



Sources: IEA, 2012c and IEA analysis.

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC 2011) assessed the scenarios literature for hydropower and found that deployment of hydropower could reach as high as 9 770 TWh in 2050. This is the highest forecast based on the 164 scenarios assessed and applying the most ambitious emissions reduction targets. The median contribution of hydropower in the stabilisation scenarios is about 5 300 TWh, increasing to 6 400 TWh at the 75th percentile. The hydropower industry forecasts a hydropower market potential of more than 8 700 TWh/y to be reached in 2050 (IJHD 2010).

Regional scales

Africa

The African continent has the largest proportion of untapped hydropower potential, with only 8% currently developed. Most of this potential lies in Africa's many regional and cross-boundary river basins, including the Congo, Nile, Niger and Zambezi rivers.

Regional instability remains one of the main impediments to development in Africa, especially for large projects requiring extensive cross-border transmission. Grand Inga on the Congo River, potentially the largest hydro development in the world, has suffered many false starts. The necessary infrastructure to generate and transfer power is immense and will affect a major part of the continent.

Regulatory challenges to this and other large projects include the prevalence of state monopolies, lack of integration of water and power policies, and grid access.

In contrast to the large projects, many smaller projects are currently being successfully developed. Resource development in Africa is driving much of this with the number of independent power producers (IPPs) increasing in some countries. Many resource companies are also looking to develop their own hydropower to reduce their dependence on fossil fuels in mining operations.

While the development of large projects will remain a challenge for Africa in the foreseeable future, smaller hydropower projects are easier to fund, have smaller social impacts and shorter project development cycles. In conjunction with increased investment in the strengthening and maintenance of regional distribution and transmission networks, these initiatives can have significant impact on the short- to medium-term energy shortages on the continent.

This roadmap foresees a total hydropower capacity in Africa of 88 GW by 2050, with hydroelectricity generation reaching 350 TWh.

Central and South America

Hydropower development in Central and South America has been remarkable, especially since the 1970s, reaching 150 GW of installed capacity. About half the electricity produced in the region is water borne. This strongly contributes to the region having the cleanest energy mix in the world (26% of primary energy supply from renewable sources), particularly with respect to electricity production. The available but unexploited hydropower potential is approximately 540 GW, distributed among almost all countries of the region (see Appendixes).

Hydropower projects play a major part in the expansion plans of many countries in the region. In addition to economic, environmental and technical factors this is due most importantly to the countries' advanced energy planning. Generally, the conditions of hydropower development are favorable in Latin America and the Caribbean. Many countries have established legislation in this area, with guidelines for negotiation and consultation with affected communities.

Historically, the Brazilian electric generation system was developed largely based on hydropower due to the large potential and favorable economics. The current hydropower generation system comprises large reservoirs, capable of multi-year regulation, arranged in complex cascades distributed over several river basins. The interconnected transmission system was developed to take advantage of the hydrological synergies, and a complementary thermal system mitigates possible unfavorable hydrological conditions. In 2010, hydropower provided 78% of the installed capacity of 103 GW (MME/EPE 2011). Brazil's 10-year Energy Plan 2020 (PDE 2020) predicts hydropower capacity increasing to about 115 GW. Although the contribution of hydropower to the electricity generation will fall from 80.2% to 73%, the share of renewable resources will be kept roughly constant, as a result of growing wind power and cogeneration using sugarcane bagasse.

Other South American countries that are actively developing hydropower include:

- Chile: by 2021, some ten hydroelectric projects are planned, which would increase the installed capacity by 1 917 MW. In addition, the Aysen hydropower complex, which would provide 1 600 MW, is expected to be incorporated into the system after 2021.
- Colombia: the expansion plan from 2011 to 2025 aims to increase the installed capacity by 7 914 MW, of which 6 088 MW will be attributed to HPP projects (including the Ituango power plant with a capacity of 3 000 MW).
- Costa Rica: the country is committed to being carbon neutral in 2021; the development of hydropower is essential to achieve this goal. By 2021 the installed generation capacity is due to increase by 1 613 MW, of which 1 471 MW will be from hydropower sources and the rest based on wind energy conversion.
- Ecuador: the government plans to add 4 820 MW of total installed generation capacity by 2032, of which 2 590 MW (54%) will be HPP. The Coca Codo Sinclair HPP project, to supply 1 500 MW, is due to start generating in 2016.
- Peru: a significant increase in hydropower capacity is expected, with the installation of 1 153 MW of hydropower plants, in a total capacity increase of 3 163 MW.

Latin America and the Caribbean have relevant experience in the use of water resources shared by several countries, illustrating exemplary regional energy integration. Major projects in the basin of Rio de la Plata have taken advantage of two major rivers (Parana and Uruguay). Bi-national hydropower projects not only provide energy benefits to partner countries of the enterprises, but have also driven the development of areas of influence near the power plants. Resulting programmes have provided schemes of social support to local communities, protection of species and the environment, and the development of tourism recreation and productive activities. Itaipu Binational, a joint venture between Brazil and Paraguay (with a nominal capacity of 14 GW) supports a social-environmental initiative focused on conservation of natural resources, quality and quantity of water, and on people's quality of life under a programme called *Cultivating Good Water*. The programme also includes a technology park that is becoming an R&D reference centre for many clean technologies (*e.g.* biogas, fuel cells, electric vehicles), and an educational initiative through the University of the Latin American Integration (UNILA). Regarding future development, the Garabi-Panambi project will be implemented in the Uruguay River between Argentina and Brazil with a capacity of 2 200 MW, distributed in a complex of two hydropower plants coming into operation in 2020. In the same basin of the Rio de la Plata, the Corpus Christi project (with a design capacity of 2 900 MW) will be a joint project of Argentina and Paraguay.

On the basis of the 2DS, this roadmap foresees a total capacity in central and south America of 240 GW by 2050, of which 130 GW will be in Brazil alone. Hydroelectricity generation would reach 1 190 TWh, again more than half in Brazil.

The official Brazilian projections for 2030 and 2050 are significantly higher than those of the 2DS, at 164 GW and 827 TWh for 2030, and 180 GW and 905 TWh for 2050. These are based on different assumptions for economic growth and electricity consumption (MME/EPE, 2007, 2011).

North America

The US Department of Energy (US DOE) aims to double hydropower capacity through upgrades to, and optimisation of, the existing facilities, powering non-powered dams and developing small hydropower facilities. A memorandum of understanding (MoU) for hydropower was signed in March 2010 between the US Department of Energy, Department of Interior and Army Corps of Engineers with a focus on increasing generation from federal hydropower facilities and reducing environmental impacts.

Some regions of the United States are increasing variable renewable penetration by more than 30%, typically through wind power and increasing amounts of solar photovoltaics. Under aggressive clean energy deployment scenarios – such as the 15% to 18% solar penetration targets of US DOE's "Sunshot" and "20% Wind by 2030" goals – installation of PSP and modernisation of the existing reservoir hydropower will be critical for integrating growing amounts of variable renewable energy.

In addition to laying out a strategic vision from which to pursue zero-carbon clean energy from hydropower, the United States is assessing the potential impacts of climate change on hydropower production from federal facilities. Its *Climate Change Assessment Report* is reassessed every five years to estimate the hydrological impacts of climate change, and their resulting influence on the capabilities of US hydropower.

Canada is already producing about 60% of its electricity through hydropower. The country currently exports around 40 TWh per year to the United States, about 1% of the US electricity supply. Canada is entering a significant period of new hydropower development. A Canadian Hydropower Association study estimates there remains 163 GW of undeveloped hydropower potential, more than twice the current capacity of about 74 GW. This potential is distributed evenly across the country. At present, 14.5 GW of new hydropower facilities are under construction or in advanced planning states and expected to come online over the next 10 to 15 years.

This roadmap foresees a total hydropower capacity in North America of 215 GW by 2050, with hydroelectricity reaching 830 TWh.

Asia

China is experiencing an impressive deployment of new hydropower capacities. Its hydropower generation jumped from less than 400 TWh in 2005 to an estimated 735 TWh by 2011, and is expected to increase to almost 1 100 TWh by 2017. Chinese hydropower generation will likely pass the 1 500 TWh mark by 2035 or before (IEA, 2012c). In the next 20 to 30 years, hydropower will remain second after coal within the Chinese energy mix. PSP is also developing quickly in China, with targets of 30 GW by 2015 and 70 GW by 2020 (Gao, 2012).

Although a factor, the quest for electricity is not the only driver: flood control and navigation services are equally important in China. Five state-owned companies are responsible for most investment in electricity generating capacities. They are usually given responsibility for all dams on a single river basin, thus allowing for harmonised management of the resource.

In India, the Central Electricity Authority has mapped out hydropower resources by river basin, ranking the attractiveness of potential hydropower sites (CEA, 2001), for a total of 148.7 GW in 399 hydro schemes – plus 94 GW in 56 possible pumped storage projects. In May 2003, the government launched the "50 000 MW Hydroelectric initiative" of 162 projects, of which 41 were storage-based and 121 RoR. Their development faces several constraints such as delays in environmental approvals, forest clearance, lack of infrastructure (roads, power and reliable telecommunication systems), and issues relating to corruption, land acquisition, benefit sharing, resettlement and rehabilitation. Development of transmission systems to connect hydro projects located in remote areas is also challenging. To overcome resistance against dam development, state governments may prefer run-of-river schemes to reservoir storage schemes, thereby forfeiting the premium value that hydropower provides as peak power and water security for irrigation and drinking water use.

Despite the region's rich resources, South Asia continues to face power shortages that constrain economic growth. Tremendous scope exists for co-operation in energy. Three nations bordering India have rich hydropower potential far in excess of their domestic needs: Nepal (potential of 84 GW), Bhutan (24 GW) and Burma (100 GW). India, with its large gap between demand and supply, offers a ready market. This roadmap foresees a total hydropower capacity in Asia of 852 GW by 2050, half in China and one quarter in India, with hydroelectricity reaching 2 930 TWh.

Europe

At present, only about half the technically feasible potential for hydropower in Europe[3] has been developed. The additional potential could be 660 TWh a year, of which 276 TWh would be in EU member states and more than 200 TWh in Turkey (Eurelectric, 2011).

In countries that have already extensively developed hydropower, environmental regulations and economic considerations may limit its further expansion, and not all technical potential will likely be harvested. For example, hydropower in France already generates 67 TWh/y on average. The overall technical potential has been assessed at 95 TWh/y, but taking the strongest environmental protection in full account brings the total to 80 TWh – still a 19% increase from current level (Dambrine, 2006).

EU member states have a common target of 20% renewable energy use by 2020. The European Union has also introduced the Water Framework Directive to turn rivers back to their original environment as far as possible, with a focus on pollution reduction. In certain rivers, this will result in reduced hydropower generation capacity due to increased compensation flow (*i.e.* the body of water bypassing the HPP). A significant barrier for future development of hydropower in Europe is the lack of harmonisation between EU energy policy and various EU water management policies. This creates substantial regulatory uncertainties, which are amplified by highly variable national implementation of these conflicting EU legislations. To promote implementation of renewable energy schemes, many EU countries have introduced large economic support programmes, such as feed-in tariffs. Some of these systems include smaller-scale hydropower projects, but most exclude larger-scale hydropower projects.

In this context, reservoir HPP and PSP could facilitate the expansion of variable renewables. Several countries are strengthening or creating ties with Norway, which has considerable hydropower potential. Norway's Statnett and UK's National Grid, for example, are jointly developing a project to construct a HVDC cable between Norway and Great Britain. The North Sea Offshore Grid Initiative aims to provide energy security, foster competition and connect offshore wind power. It will benefit from Norway's HP capacity. Reservoir and cascading HPP in the Alps or the Pyrenees could also play an important role in backing up the expansion of wind power and PV.

PSPs, previously used for night pumping and diurnal generation, are now used for frequent pumping and generation during either day or night, as a result of the expansion of variable renewables.

3. In this section, Europe does not include Eurasia and Russia; the region has a hydropower capacity of 249 GW by 2009.

Europe is at the forefront of the development of new PSP, either open-loop or pump-back. Germany, for example, which has very little conventional hydropower, already has about 7 GW of PSP and will add 2.5 GW by 2020. Within the same time frame, France will add 3 GW to its current 5 GW and Portugal will quadruple its 1 GW capacity. Italy, Spain, Greece, Austria and Switzerland also plan to develop new PSP. According to their National Renewable Energy Plans, EU countries will increase their PSP capacities from 16 GW in 2005 to 35 GW by 2020. Storage volumes, however, differ markedly between countries. In Spain, PSP can be used to offset several-day periods of low generation from renewables; in the United Kingdom, storage is limited to shifting generation by several hours to better match demand.

European islands, such as the Spanish El Hierro or the Greek Ikaria, now host the first PSP directly coupled with wind power. Larger islands may have larger ambitions. Ireland, with many U-shaped glacial valleys close to its windy west coast is considering an "Okinawa-style",[4] seawater PSP including a dam that would close one of these valleys. The 700 MW base, 2.2 GW peak load power station would be fed by 18 directly coupled 100-MW wind farms. It would send power to the national grid, and export to the United Kingdom and Europe.

This roadmap foresees a hydropower capacity in Europe of 310 GW by 2050, with hydroelectricity reaching 915 TWh.

Russia and Eurasia

Of the current 47 GW of hydropower capacity in Russia, almost 10 GW are from units more than 40 years old, 7 GW are under construction and 12 GW more are planned. Under Russia"s Energy Strategy to 2020, the share of hydropower generation within the energy mix is to remain at its current level of about 20%.

In Tajikistan, 5 GW of hydropower capacity are currently in operation, providing 95% of the country's electricity, although 40% of it is absorbed in aluminum production. The identified potential is vast: 14 plants of a total capacity 18.7 GW could be developed on the Panj River alone. Kyrgyzstan also has a vast potential, of which only about 10% has been developed so far. Better regional co-operation and greater support from the international community may be required for any significant development.

This roadmap foresees a hydropower capacity in Russia and Eurasia of 145 GW by 2050, with hydropower reaching 510 TWh, of which almost 75% will be in Russia.

The broader context of renewable deployment

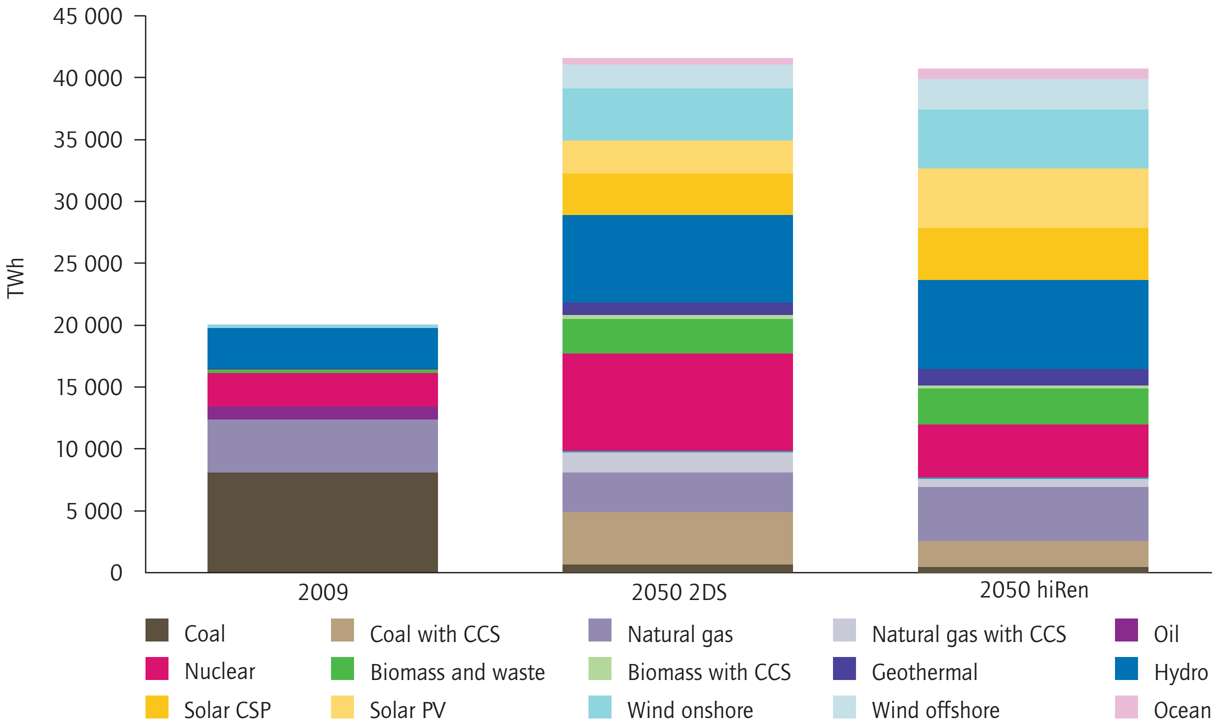
It is interesting to relate the projections given above to the more general projections of the fuel mix in power generation under the various scenarios of *ETP 2012*, as this clarifies the twin roles of hydropower – providing clean, renewable electricity and enabling the grid integration of variable renewables. The 2DS shows a strong trend toward diversification: renewables together provide 57% of electricity. The most variable renewable sources – wind, solar photovoltaics (PV) and marine energies – increase the most, contributing to 22% of the total supply.

ETP 2012 also provides variants of the 2DS. One of particular relevance for renewable deployment is called the 2DS Hi-REN (high renewables). In this scenario, an expanded role of renewables compensates for a lower deployment of nuclear energy and a delay in the development of carbon capture and storage (CCS) technologies (Figure 12). The share of variable renewables (solar PV and wind) would increase from 22% to 30%, making the flexibility and storage capabilities of hydropower even more valuable.

Reservoir hydropower, when available, can integrate variable renewables thanks to its flexibility. Where the potential for reservoir hydropower is limited, pumped storage may represent the most cost-effective option to avoid curtailing significant amounts of renewables when production exceeds need.

4. The first demonstration of seawater pumped storage worldwide was the 30 MW Yanbaru project in Okinawa.

Figure 12: Fuel mix in power generation and in the 2DS, 2009-50



Source: IEA, 2012c.

Pumped storage hydropower deployment

Technical potential

There is no global study on the technical potential of pumped storage hydropower, but its potential is quite significant, as PSP can be built from existing reservoir HPP (Lacal Arantegui *et al.*, 2012). Creating an additional, relatively small reservoir near existing HPP plants is often possible in mountainous areas. Both reservoirs may already exist in cascading HPP systems – only turbines need to be replaced or completed with pumps and appropriate pipework. This may open options for much larger storage capacities, as natural reservoirs can be extremely large, as is the case for Lakes Erie and Ontario on the Canada-US border. Pumping seawater to upper reservoirs on cliffs, or freshwater in closed-loop systems (*i.e.* independent of any river basin), offers considerable additional possibilities. Finally, where there is no natural head, entirely artificial systems may be constructed – such as offshore "power islands" or on plains or plateaus on shore (as described below in the section on technology).

Some PSPs are currently being used as low-frequency storage; with larger penstocks (flow regulation equipment) and pump turbines, they could provide considerable daily services to support variable renewables. One example is the artificial Hongrin Lake in Switzerland: the power station has 240 MW capacity, but the energy storage potential is considerable, with about 124 GWh stored in the upper lake (the lower reservoir is Lake Leman). Its current use is equivalent to emptying the upper reservoir seven times per year and refilling it five times with water pumped up, and twice with natural flow, generating each year 730 GWh. With additional pump turbines and larger penstocks, it could provide much greater capacity – as much as 10 GW for 12 hours. Under this formulation, the PSP plant would annually shift up to 40 TWh from generation peak to demand peak (Bonnelle, 2012). For reference, several PSP plants in the world already have capacities over 2 GW.

Short-term deployment

Many PSP projects are currently under development, mostly in China and Europe. This includes modernisation, upgrading or full redevelopment of 30- to 50-year-old PSP, and gradual expansion of recent plants. The Kannagawa PSP in Japan was commissioned in 2005 with one 470 MW pump turbine; five more pumps will be come on line in the coming years. PSP already plays a growing role to back wind power in several countries, such as Germany, Spain and Portugal (Box 2).

Box 2: Hydro facilitating wind power in Portugal

Portugal must address the variability of wind power, which provides 17% of its electricity but has delivered up to 70% of all electricity in a single day (13 November 2011). The Iberian Peninsula has great hydropower potential but poor electricity connections with neighbouring countries. Portugal's currently installed HPP capacity totals 5 180 MW, which it intends to almost double by 2020. It also has about 1 245 MW pump-back PSPs, which it intends to quadruple in the same time frame, to support its continuous wind power deployment. Of the 1 959 MW of added hydropower capacity under construction, 1 367 MW include capacity for pumping.

The need for greater flexibility, which historically arose from the rigidity of some thermal power plants, is driving this expansion in many countries. This is only in part technical; economically, operating heavily capitalised plant (originally designed for base load) to accommodate variations in demand dramatically cuts its profitability. Too rapid and frequent variations may create costly wear and tear, and reduce the plant's technical lifetime or require costly repairs. Yet large amounts of variable renewables will only increase this need for flexibility.

The economics of PSP have paradoxically deteriorated in the last few years in many countries (see section on economics, below), slowing deployment. Three years ago, the global capacity was expected to exceed 200 GW by 2014 (Ingram, 2009) but this level is now unlikely to be achieved for several more years.

Long-term deployment

Assessing the long-term global deployment of pumped storage hydropower is complex. Current visions of a very large-scale deployment of renewables with minimal energy-related CO_2 emissions tend to assume that covering demand peaks and ensuring electricity generation during long periods of very low wind or sun would best be achieved by combining some electricity storage with a large base of conventional, cheap peaking plants with quite small load factors (IEA, 2011b). In fact, hydropower capacities might be adapted to respond to this need, *i.e.* increasing the capacities of existing or new-built HPPs might enable their more frequent use as peaking plants. PSP provides the largest electricity storage volumes and capacities, but projects are capital intensive, and investments need to be made where the capacity created will be profitable (IEA, 2012c).

A simplified approach builds on ETP 2012, assuming that PSP remains the backbone of electricity storage capabilities. The ratio of current PSP capacity to total electric capacity very much depends on the characteristics of each electricity system: it is very low where hydropower dominates, but high in less flexible systems. PSPs currently represent about 2% of capacities in North America, 3% in China, 5% in Europe, and 11% in Japan, and these proportions are increasing. A conservative approach would be to increase only the lowest of these percentages, and only slightly. This "low" estimate (Table 4) would lead to about 400 GW by 2050 – close to a trebling of current PSP capacities.

The Hi-REN variant, which in some regions (notably Europe and the United States) leads to a greater proportion of variable renewables while not significantly increasing the balancing role of reservoir hydropower, would likely call for more PSP. This would lead to about 700 GW PSP by 2050, a quintupling of current PSP capacities, while still keeping the percentages of PSP under today's level in Japan. Noting that some experts envision even higher deployment levels of PSP (*e.g.* Lempérière, 2010), this roadmap suggests a range of 400 GW to 700 GW PSP capacities by 2050.

Table 4: Expected PSP capacities in 2050

		China	United States	Europe	Japan	Rest of world	Total
Low estimate (2DS)	VRE % total energy	21%	24%	43%	18%		
	Hydro % total energy	14%	6%	13%	12%		
	PSP/total capacity	4%	4%	6%	11%	2%	
	GW	**119**	**58**	**91**	**35**	**109**	**412**
High estimate (Hi-REN)	VRE % total energy	34%	37%	48%	33%		
	Hydro % total energy	15%	6%	11%	13%		
	PSP/total capacity	5%	8%	10%	12%	3%	
	GW	**179**	**139**	**188**	**39**	**164**	**700**

Note: For both low and high estimates, the first two lines indicate the percentage of variable renewable energy, and of hydroelectricity, relative to total energy in the electricity mix, as resulting from the 2DS or the Hi-REN modelling; building on this information as explained in the main text, the third line shows this roadmap's assumption of the possible share of pump-storage capacities over total electric capacities. The fourth line expresses these results in GW.

Contribution to CO_2 abatement

The deployment of sustainable hydropower as envisaged in this roadmap would by 2050 avoid the annual emission of 1 billion tonnes CO_2 in comparison with the 6DS of *ETP 2012.* This represents 2.4% of the total CO_2 savings of the 2DS, and 6.2% of the savings from the power sector.

The impact of hydropower deployment on climate change mitigation is more significant than these numbers suggest, however. First, there is already very significant hydropower deployment in the 6DS, as this is the most mature and lowest-cost renewable energy technology. Without the 75% increase in hydropower generation of the 6DS, and assuming substitution with a mix of gas and coal, by 2050 the already considerable emissions in this scenario would swell by an additional 2 billion tCO_2 per year. Further, reservoir and pumped-storage hydropower are instrumental in facilitating the management of increasing amounts of wind power and solar PV electricity, and the associated CO_2 emission reductions.

Sustainable hydropower development

Historically, hydropower development has had many drivers, dependent on economic and social circumstances in various regions of the world. Meeting future scenarios, as outlined in this roadmap, requires the application of internationally recognised environmental and social standards. The most important barriers and enabling factors are shown on Table 5.

Table 5: Possible barriers and enabling factors for hydropower development

Barriers	*Enabling factors*
Environmental issues	Development based on following internationally accepted sustainability approaches or protocols. Integrated river basin approach.
Socio-economic issues	Valuation of benefits, market reforms.
Public acceptance	Expanded scope of hydropower to include multi-purpose benefits.
Financing	Innovative financing schemes with public risk-mitigating instruments.

Environmental issues

Environmental issues identified in the development of hydropower include:

- safety issues;
- water use and water quality impacts;
- impacts on migratory species and biodiversity;
- implementing hydropower projects in areas with low or no anthropogenic activity;
- reservoir sedimentation and debris; and
- lifecycle greenhouse gas emissions.

The question of the size of projects has sometimes been associated with the importance of their environmental impacts – this issue is briefly addressed below, as well as the environmental issues associated with pumped storage hydropower.

Safety issues

Hydropower is very safe today. Some dam failures occurred before 1920 in Europe and North America and before 1980 in Asia; most of these were storage, mine waste or diversion dams that did not have hydropower facilities. Losses of life have been very rare in the last 30 years, whereas the population at risk has been significantly reduced through the routing and mitigation of extreme flood events.

Water use and water quality impacts

As hydropower uses water as its fuel, by running it through turbines and discharging the identical volume into a water body further downstream, the hydropower production process in itself does not consume water. However, additional evaporation may occur from the water stored upstream, which has recently been proposed as water consumption of hydropower. A methodology to quantify additional evaporation caused by water stored for hydropower is required, as evaporation will take place even in the absence of the hydropower facility. As the water stored will typically be for multiple purposes, a methodology is also required to apportion water consumption to each of the purposes. In 2010, the International Hydropower Association (IHA) initiated a first scoping report on the topic and surveyed its membership on evaporation measurements. The work to establish the evaporation impact of water storage infrastructure is on-going (especially for water-scarce catchments). The method to allocate losses to each of the services from such water storage will be addressed in future work.

The impact of hydropower plants on water quality is very site specific and depends on the type of plant, how it is operated and the water quality before it reaches the plant. RoR plants are often used to improve dissolved oxygen levels and retain floating debris for disposal. Where there is significant waste entering the reservoir from upstream sources, managing the water quality in the reservoir may be very challenging.

Dissolved oxygen (DO) levels are an important aspect of reservoir water quality. Large, deep reservoirs may have reduced DO levels in bottom waters, where watersheds yield moderate to heavy amounts of organic sediments. For projects with bottom intakes, this low DO water may create problems both within and downstream from the reservoir, including possible damage to aquatic habitat. This can be mitigated by multi-level water intakes in reservoirs, and by new turbine designs (see Technology Improvements).

Impacts on migratory species and biodiversity

Older dams with hydropower facilities were often developed without due consideration for migrating fish. Many of these older plants have been refurbished to allow both upstream and downstream migration capability. New purpose-built fish ways and steps reduce the barriers to fish movement in the altered river course. Extensive research has been carried out to reduce mortality as fish pass downstream through the hydraulic turbines, leading to significant improvements in turbine design. In recent years, minimum gap runner[5] (MGR) technology has been documented to achieve fish survival rates in excess of 95% for large axial flow units in the field. New designs, such as the Alden turbine, expand the range of fish-friendly units to smaller turbine applications.

Hydropower plants also modify downstream flow regimes, influencing sediment-carrying capacity and erosion. These changes may significantly affect natural aquatic and terrestrial habitats in the river and along its shores. Sudden water releases constitute a risk for wildlife and humans. All these effects can be mitigated by thorough flow-management programmes (IPCC, 2011).

Hydropower development may also affect species other than fish, including mammals, birds and invertebrates, although the changes are not necessarily negative. The assessments of hydropower potential should address these issues in the early planning phases. The natural value of certain areas might be such that they must be used with great care or left untouched (IPCC, 2011).

5. The runner in a hydropower turbine is the rotating element.

Implementing hydropower projects in areas with low or no anthropogenic activity

The creation of reservoir HPP or ROR plants often involves large public works in remote areas, and this activity may last for several years. Hundreds or thousands of workers need to live nearby, and this usually requires large settlements for workers and their families with supporting infrastructure including schools, places of worship, recreational facilities and hospitals.

The impacts and implications of these activities strongly depend on the existing level of anthropogenic activities. In inhabited areas they may have impacts on population, which are further described in the section on socio-economic issues. Nevertheless, sustainable hydropower development can also be used to foster social and economic development, especially for local communities.

In areas with low or no anthropogenic activity the primary goal is to minimize the impacts on the environment. An innovative approach to allow the implementation of HPP projects in areas with low or no anthropogenic activity is being developed in Brazil, especially in river basins located in the northern region. Referred to as the "offshore platform" HPP approach (Melo *et al.*, 2012), it aims to keep the impact restricted to the plant site, with minimum interference over forest domains at dams and reservoir areas, *e.g.* by avoiding the development of villages or cities after the construction periods. Plant construction excludes large and permanent settlements for workers; auxiliary access and roads are reduced to strict minimum; forest and affected areas are recovered during construction; and the plant will be – as much as possible – remotely-operated by using automation technologies and a small number of staff in turn-over labour periods, similarly to offshore platforms for the oil and gas industry. Therefore, in this approach the anthropogenic footprint impact on the project area will be reduced and the "offshore platform" hydropower plant will be an enabler of permanent environmental conservation.

Reservoir sedimentation and debris

All rivers transport sediments, such as sands, gravels, silt and clay particles, which tend to be deposited when water reaches a reservoir. This may change the overall geomorphology of the river and affect the reservoir, the dam/powerplant and the downstream environment.

Reservoir storage capacity can be reduced, depending on the volume of sediment carried by the river. Flushing sediments through low-level outlets in the dam can alleviate this situation, but can lead to adverse impacts downstream. Abrasive sediments passing through turbines can also damage them. Downstream impacts can range from scouring of channels and damage to structures, on the one hand, to enhancement of fish spawning areas on the other.

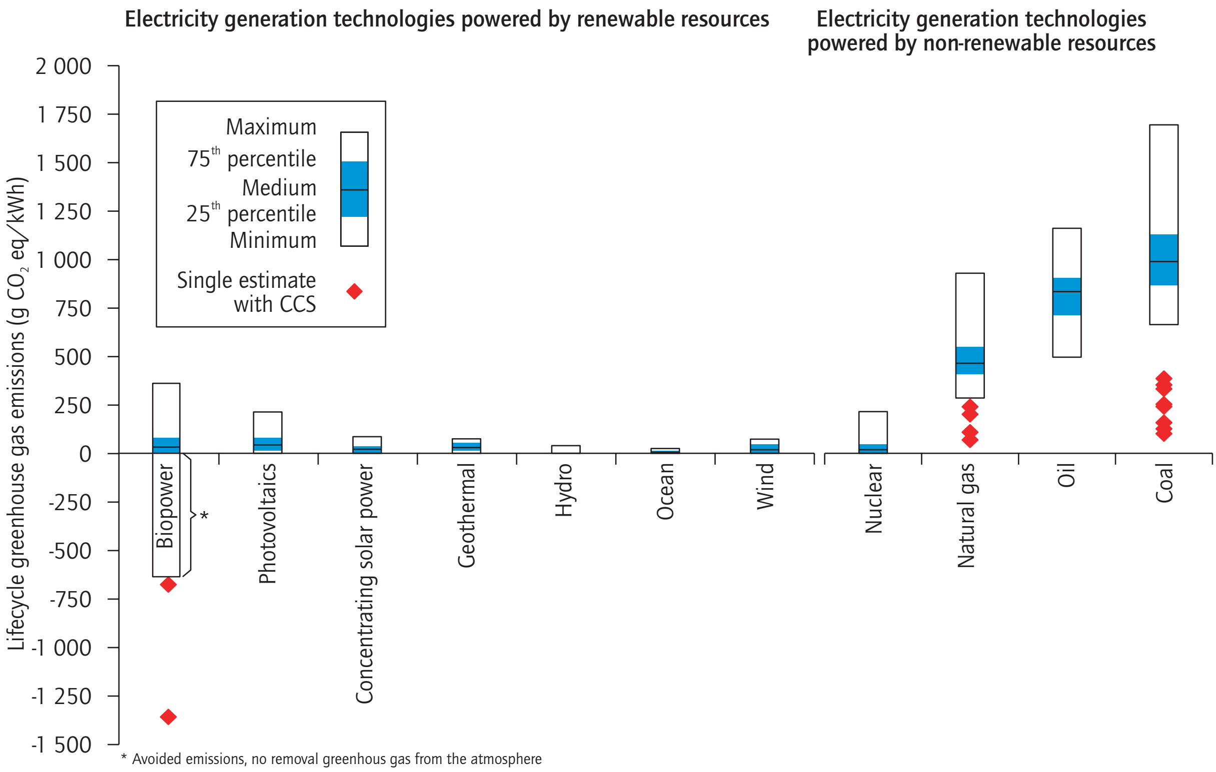
Sedimentation and debris issues are unique for each reservoir hydropower project and need to be considered carefully to ensure the impacts are managed appropriately.

Life-cycle greenhouse gas emissions

Life-cycle greenhouse gas emissions from hydropower originate from construction, operation and maintenance, and dismantling. Excluding possible emissions from land-use related net changes in carbon stocks and land management impacts, these emissions are, per kWh, one to two orders of magnitude lower than life-cycle GHG emissions from generating technologies powered by fossil fuels (Figure 13).

Possible emissions from reservoir hydropower have attracted attention in recent years. Construction and operation of artificial reservoirs introduce different regimes of mass transport and storage

Figure 13: Estimates of lifecycle GHG emissions in electricity generation (excluding land-use changes)



	Biopower	Photovoltaics	Concentrating solar power	Geothermal	Hydro	Ocean	Wind	Nuclear	Natural gas	Oil	Coal
Count of estimates	222 (+4)	124	42	8	28	10	126	125	83 (+7)	24	169 (+12)
Count of references	52 (+0)	26	13	6	11	5	49	32	36 (+4)	10	50 (+10)

Source: IPCC, 2011.

in the flooded areas. The main mechanisms of carbon transportation in the watershed and at the reservoir are:

- gas fluxes of CH_4 and CO_2 through diffusion and bubbling from the lake surface to the atmosphere;
- leaching of organic carbon (dissolved and particulate) from watershed soils to tributary rivers;
- carbon fixing by photosynthesis;
- decomposition of pre-existing biomass at the bottom of reservoirs, generating CH_4 and CO_2 in the water;
- carbon fossilisation in the sediment at the bottom of reservoir; and
- loss of carbon sinks (*e.g.* wetlands and forests) due to alteration of flow patterns and land use.

In the 1990s, a number of published GHG measurements taken from hydropower reservoirs indicated that some hydropower plants could contribute to GHG emissions, especially in the first few years after impoundment. However, it appears difficult to generalise estimates of lifecycle GHG emissions for HPP across climatic conditions, pre-impoundment land-cover types and hydropower technologies. An important issue is the multi-purpose nature of most reservoir HPPs, and allocation of total impacts to the several purposes.

Most studies focus on gross emissions. Characterising a reservoir as a net GHG emitter implies consideration of emissions that would have occurred without the reservoir, about which there is currently no consensus. All freshwater systems, whether natural or manmade, emit GHGs due to decomposing organic material. They also bury some carbon in sediment. Within a given region with similar ecological conditions, reservoirs and natural water systems produce similar levels of CO_2 emissions per unit area. Sometimes either type absorbs more than they emit.

In 2008, the International Hydropower Association (IHA) and UNESCO's International Hydrological Programme (UNESCO-IHP) launched the UNESCO/IHA GHG Research Project – entitled *GHG Status of Freshwater Reservoirs*. This project aims to improve understanding of the impact of reservoirs on natural GHG emissions and of the processes involved, and to help fill knowledge gaps in this area. The project is run through a consensus-based, scientific approach, involving collaboration among many institutions and experts. It has led, as a first outcome, to the publication of the *GHG Measurement Guidelines* (IHA, 2010). A framework for an initial mitigation guidance document is under development.

In parallel, IEA Hydro started a new research project on managing the carbon balance in freshwater reservoirs. The objectives of the comprehensive work programme are to: increase knowledge about processes connected to reservoir GHG emissions; establish guidelines for planning studies on the carbon balance in reservoirs; standardise GHG flux evaluation methods; and develop an accepted methodology to measure and manage the carbon balance in reservoirs. The project is managed by Brazil's Electric Energy Research Center (CEPEL).

The multi-level water intake and turbine design measures mentioned above that can help avoid reduced DO levels can also reduce methane formation and, hence, GHG emissions.

Impacts of project size

Some environmental NGOs express strong preference for smaller-scale HPP over larger-scale HPP. This is an over-simplistic approach. Environmental and social impacts of larger-scale HPP are likely to be greater than those of smaller-scale HPP considered individually, but this may not be the case if similar capacities or energy production totals are compared. The cumulative impacts of many smaller-scale plants might be equivalent to or even larger than those of one single larger plant generating the same power output. In fact, some other NGOs consider that sustainability issues are actually more under scrutiny and control in fewer large plants than a myriad of smaller plants. In any case, all HPPs should be evaluated on their sustainability performance, since the latter does not really depend on size.

Environmental footprint of PSP

The possible environmental impacts of pumped storage plants have not been systematically assessed, but are expected to be small. The water is largely reused, limiting extraction from external water bodies to a minimum. Using existing dams for pumped storage may result in political opportunities and funding for retrofitting devices and new operating rules that reduce previous ecological and social impacts (Pittock, 2010). PSP projects require small land areas, as their reservoirs will in most cases be designed to provide only hours or days of generating capacities.

Socio-economic issues

Hydropower technology provides great opportunities to develop a sustainable energy supply. It offers competitive generation costs, low GHG emission factors, and the highest energy payback ratio of all energy technologies. However, like any other significant change within natural settings, hydropower has implications for landscape, wildlife and biodiversity, population settlement, indigenous people, ethnic minorities, cultural heritage, health and water quality, some of which can be negative. With careful planning and implementation these issues can be avoided, minimised, mitigated or compensated. In any case, the considerable advantages and benefits arising from projects should be shared with stakeholders. The IEA has conducted research into hydropower and the environment in collaboration with private agencies, governmental institutions, universities, research institutions and international organisations and drawn on more than 200 case studies. As a result, the IEA Implementing Agreement on Hydropower Technologies published five peer-reviewed reports between 1996 and 2000 (IEA Hydro, 2000a, b, c, d, e), which demonstrate the benefits of hydropower and appropriate approaches to sustainability.

Managing socio-economic changes is one of the most important aspects in the development of local scale sustainable hydropower projects. The process must cover all the issues, be transparent and have a full outreach programme with all the affected people, as exemplified by the Nam Theun 2 project (Box 3). This will include identification of the potential ways people could be affected and how the communication process will be handled, such as surveys and public hearings. Such effort is particularly important for any resettlement programme, which the project should fully fund. Resettlement issues should be considered from the early planning stage. In the feasibility studies, an economic assessment of required resettlement, including costs for improvement in living standards, should be established together with the development of resettlement plans incorporating compensation and monitoring procedures. In construction and operation phases, monitoring is undertaken in order to verify if commitments made have been delivered and to identify any new issues or concerns.

Public acceptance

Public acceptance is crucial to any hydropower project because the perceptions that shape public opinion influence the regulatory context (permits, approvals, licences, etc.).

Box 3: The Nam Theun 2 project: a model for sustainable development?

Nam Theun 2 (NT2) is a cross-border project consisting of dams with hydropower facilities having an installed capacity of 1 070 MW (1 000 MW for export to Thailand and 70 MW for domestic use in Laos and the management of the project's environmental and social impacts). Following a feasibility study initiated by the World Bank, it is the largest foreign investment by the Lao People's Democratic Republic (Lao PDR), the world's largest private-sector financed cross-border HPP project, and a significant step in the co-operation between Lao PDR and Thailand. Delayed in particular by the Asian financial crisis, the project took 20 years to be completed after the feasibility study initiated by the World Bank in 1989.

The environmental and socio-economic issues associated with NT2 have been studied and evaluated comprehensively since the early 1970s by the project sponsors, Lao PDR, NGOs, consultants and multilateral development institutions. The project has been designed to meet and often exceed the applicable World Bank and Asian Development Bank guidelines on E&S issues. A proportion of its revenues will be used for poverty reduction and environmental protection. The legal commitment, written into the Concession Agreement, to improve the incomes of resettled villagers, sets a new standard for hydro schemes. Various independent monitoring agencies work to ensure these obligations are strictly followed. NT2 was voted the top hydroelectric power project of the year 2011 in a *Global Energy Magazine* poll.

Despite numerous examples of excellent water resource projects with reservoirs (some including hydropower plants) that have benefited many communities, the latter decades of the last century were marked by substantial opposition to large-scale dam development. In 2000, the *World Commission on Dams* (WCD, 2000) formulated an influential set of recommendations that led to repositioning of the industry. Since WCD 2000, hydropower developments have placed more emphasis on investigating, implementing and communicating sustainability aspects, and incorporating multi-purpose benefits.

A large body of opinion remains unfavourable to hydropower. Improved communication is an important means to challenge perceptions and demonstrate steps that the sector has taken successfully to address issues of sustainability, often with multi-stakeholder groups. Key subjects for communication include sustainability criteria and protocols, multi-purpose development, and the energy-water nexus highlighting climate mitigation benefits. Disseminating this information will help to shape policies that are crucial for the hydropower sector. It will provide information on services that are often taken for granted in the context of a licensing or relicensing process. In this context, it is important to establish the economic values associated with energy and water services provided by hydropower projects – including substantial climate change benefits.

Above all, public acceptance can only improve if hydropower projects are developed with all required attention given to environmental and social issues, and if negative impacts that cannot be avoided are minimised, mitigated or compensated. Stakeholder involvement at the various stages of project appraisal and development appear to be a prerequisite for public acceptance (Mirumachi & Torriti, forthcoming).

Sustainable approach to development

Sustainability criteria and protocols

A number of international criteria and guidelines have been developed to measure the sustainability of individual hydropower projects. In 2000, IEA Hydro published *Hydropower and the Environment: Present Context and Guidelines for Future Action*, (IEA Hydro, 2000c, d, e), with recommendations covering five areas: energy policy framework, decision-making process, comparison of project alternatives, improved environmental management and sharing benefits with local communities. In 2010, these recommendations were updated to cover important new developments and current practices in the hydropower industry, including: hydropower as a renewable and sustainable resource, hydropower as a system integrator and the multi-purpose nature of hydropower (Kaikkonen et *al.*, 2010).

Also in 2010, the International Hydropower Association published *IHA Hydropower Sustainability Assessment Protocol* (Box 4), which presents specific assessment tools for the four different stages in a project's life cycle: early stage, preparation, implementation and operation (IHA, 2010)

Box 4: IHA Hydropower Sustainability Assessment Protocol

The IHA protocol is a comprehensive tool to assess the sustainability of hydropower projects globally. It provides a rigorous, evidence-based assessment of between 19 and 23 relevant sustainability topics, depending on the development stage of the project. It is the product of a multi-stakeholder development process involving representatives from social and environmental NGOs (Oxfam, The Nature Conservancy, Transparency International, WWF); governments (notably China, Germany, Iceland, Norway, Zambia); commercial organisations (Equator Principles Group) and development banks (World Bank); and the hydropower sector, represented by IHA. Development of the protocol involved field trials in 16 countries, across 6 continents, and stakeholder engagement with nearly 2 000 people in 28 countries. Its topics cover the three pillars of sustainability – social, economic, and environmental – and include issues such as downstream flow regimes, indigenous peoples, biodiversity, infrastructure safety, resettlement, water quality, and erosion and sedimentation.

The *Sustainability Assessment Protocol* is used as a framework to produce a sustainability profile for a hydropower project. It enables all stakeholders to become better informed on the sustainability profile of a project, and to develop strategies to address any weaknesses (IHA, 2011).

River basin approach

A key aspect of sustainability is the formulation of alternatives for the partition of the total water head of a river basin, carried out in the hydropower inventory studies. The hydropower inventory is of paramount importance because the decision is taken not only for a single project but for the whole series of projects that can be developed in a river basin. These can include power system configuration, social and environmental aspects and river basin water resources plans. Such an approach is documented in *Manual for Hydropower Inventory Studies of River Basins* (MME-CEPEL, 2007), under the sponsorship of the Brazilian Ministry of Mines and Energy, funded by the World Bank and contracted to CEPEL, the Brazilian Electric Energy Research Center.

Box 5: The Brazilian approach: from river basin inventories to integrated energy planning

Brazil has developed structured planning and operation procedures for hydropower development based on a set of methodologies and studies, which interact with the planning procedures of the energy sector as a whole. In these procedures, socio-environmental aspects are considered from the first phase of expansion planning and are continuously monitored throughout the project life-cycle. The physical targets and the expansion schedules are established with a view to future auctions for the purchase of energy from new generation developments and for new transmission facilities. The development of new hydroelectric power plants involves five distinct stages: Estimate of hydroelectric potential; inventory, feasibility; basic design; and executive design. In each stage, engineering studies are balanced by assessments of energy benefits and socio-environmental impacts.

In the inventory stage, the *Manual for Hydropower Inventory Studies* outlines the process to balance energy generation, social and environmental impacts (positive and negative) and multiple uses of water. All the site selection alternatives (*i.e.* alternatives for the partition of the total water head of a river basin) are analysed and the optimum is selected according to a basic criterion of "maximising economic energy efficiency while minimizing any negative socio-environmental impacts, taking into account the positive impacts from the implementation of the hydropower plants in the basin". A computerised decision support system, SINV (CEPEL, 2008, 2011), was developed to assist the inventory studies. The manual and the SINV system have been used in several Brazilian inventory studies, e.g. the Teles Pires river basin, in Amazon region, and the bi-national study of Uruguay river basin inventory (Brazil and Argentina border), among others.

As part of project development, the purchase of energy is based on a public auction procedure. This requires a preliminary environmental license or "previous license" (LP), which itself is based on the environmental impact assessment (EIA) Report. This LP includes public hearings and water use rights. The auction winner, prior to project implementation, has to undertake further environmental studies and meet all requirements prior to obtaining the environmental operating license.

In operation, generation schedule is co-ordinated with the other generation plants in the country by the national electric system operator in order to obtain the best use of the national hydropower system. This co-ordination is done using a chain of optimization models with different degrees of detail in system representation, which are also used in the expansion planning studies of the electrical sector. These are under continuous development (Maceira *et. al*, 2002, 2008) for an integrated and sustainable expansion planning of the Brazilian energy system and, have been used not only by the Brazilian electrical sector entities but also by utilities and agents.

An example of a broad sustainability approach is the Brazilian Hydropower Practices for Achieving Sustainability, where environmental, social and economic impacts are carefully considered from the first phase of planning and continuously monitored throughout a project's life cycle (Box 5). In addition to technical and economic issues, it addresses the use of sustainability criteria to provide clear direction on how to maximise the positive and minimise the negative socio-economic impacts.

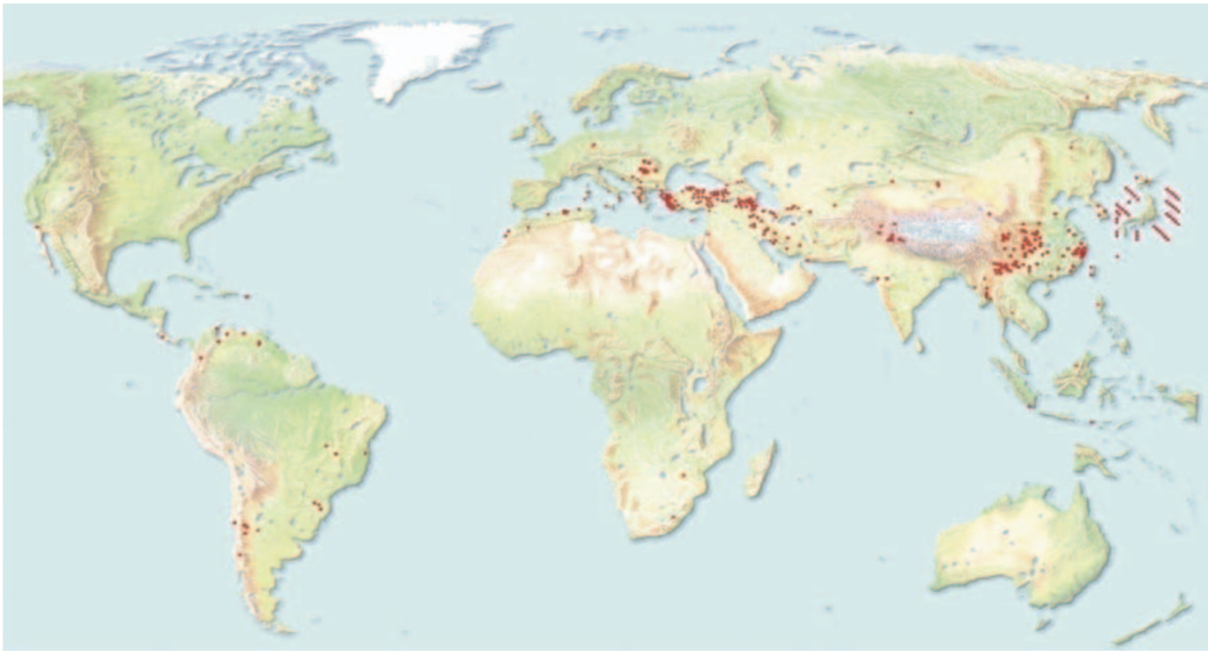
River basin planning is particularly complex for regional projects requiring bilateral and often multilateral inter-governmental agreements. An integrated approach is essential: an example is the Rapid Basin-wide Hydropower Sustainable Development Tool (RSAT), developed in the lower Mekong River Basin by the Asian Development Bank (ADB), Mekong River Commission (MRC) and World Wide Fund for Nature (WWF).

Finally, it is vital for industrial organisations involved to have well-funded and competent environment and social divisions. Human capacity on the ground is critical for a scheme to be sustainable: once the project is under construction, only the experience and ability of environmental and social staff can make and implement the correct decisions in day-to-day project management.

Multi-purpose development

Most large dams in the world today are not built for hydropower generation (Figure 14). Hydropower dams with storage reservoirs provide additional services, and in many cases would not have been justified without them, especially where there was initial opposition. The Three Gorges Dam on the Yangtze River in China, while the largest hydropower generator in the world to date, was justified primarily for the significant flood protection it provides for communities and industries downstream. Only this reduction in life safety risk for downstream populations could help to justify the large resettlement programme in the upstream flooded areas. Facilitating navigation and irrigation for agriculture purposes were also important determinants, and more recently, recreational activities and tourism are adding to the overall project benefits. However, the multiplicity of benefits does not prevent the design and management of the reservoirs from being subject to trade-offs, as not all benefits can usually be maximised simultaneously.

Figure 14: Major dams under development today – of which 60% are multi-purpose



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IJHD, 2010.

The basic approach of planning and management for multi-purpose development, at river basin if appropriate, is to find the balance between the values of water for use in different sectors of society, recognising the need to maintain the underlying ecosystem. Key users of water include energy production, domestic and industrial supply, irrigation, navigation, and water for ecosystem services. Cost-effective hydropower production has a high economic value in many river basins: it can contribute to both benefits to society and revenue to support ecosystem management and enhancement. The underlying monitoring of the water resource itself is critical to ensure that water rights for different productive uses are allocated in a transparent manner involving as many stakeholders as possible.

Elaborating multi-purpose projects can be very complex, especially where they are large and/or trans-border issues. One approach is to undertake a strategic environmental assessment (SEA), which allows any given project to be compared with potential alternatives, covering all relevant environmental, social and economic factors (Box 6).

Box 6: Strategic environment assessment of multi-purpose hydropower development

The strategic environment assessment (SEA) is an instrument to analyse impacts of hydropower development early in the planning process. It can be used to help address risks, challenges, mitigation strategies, opportunities and costs.

An SEA does not replace the traditional feasibility study and environmental and social impact assessments that are pre-requisites for project approval. Rather, it is an umbrella assessment to ensure that a project moving into the final approval and financing stage is compared with all alternative options for meeting needs in the country or region. For such a comparison, social and environmental factors are considered to be of the same level of importance as technical and economic factors.

There is an increasing trend to involve the private sector in the development and financing of new hydropower, and the SEA process can provide an overall perspective of the opportunities and risks. This is particularly important as hydropower projects are usually perceived as high risk from a political and financial perspective. The SEA process outlines key risks and opportunities for different options as well as mitigation options to be further analysed in detailed feasibility study and project design (Granit, King and Noel, 2011).

The energy-water nexus

Today there are many and varied demands on the world's water resources. The need for potable water supply and irrigation have to be fulfilled along with its use for hydropower, industry, cooling of thermal power plants, navigation, fisheries and recreation, all within the context of ecosystem integrity and water resource and flood management. Thus the future of hydropower development has to be balanced with social and environmental responsibility, integrated resource management and sound business practice.

Water and energy are closely linked, particularly in hydropower, where the generation of electricity is an integral part of water management (Granit and Lindström, 2011). Considerations driving the energy-water nexus are also tied to sustainable development. For hydropower they include:

- rapid population growth in many regions of the world and associated economic development is increasing demand for electricity and pressure on freshwater resources;
- multi-purpose hydropower schemes, providing irrigation and flood control as well as other non-energy benefits, can enhance regional development;
- hydropower development can be integrated with water supply and agriculture;
- hydropower generation is usually a domestic source of energy, and with its reliance on water can combine energy security and water security; and

- in some regions, rivers cross borders and water resource management requires transnational co-operation.

Impacts of climate change on hydropower

Hydropower producers are analysing the potential impacts of climate change on all aspects of design, safe operation, energy production, economic feasibility and overall risk exposure. With any long-term changes in climate, hydropower could be affected through:

- changes in river flow (runoff) related to changes in precipitation and melt rates of any snow pack or glacier; and changes in runoff volume, flow variability and power flows;
- changes in extreme events (floods and droughts) increasing risk and requiring design changes or dam safety improvements; and
- changes in sediment loads due to floods, changes in hydrology and use of the catchment. Additional sediment loads could increase turbine abrasion and reservoir storage volume, which in turn could affect power generation and live storage.

Quantitative forecasts of climate change impact are very uncertain (IPCC, 2011). A wide range of possible future climatic projections have been presented, with corresponding variability in projection of precipitation and runoff. At high latitudes and in part of the tropics, nearly all models project an increase in precipitation, while in some subtropical and lower mid-latitude regions, precipitation is projected to decrease. Between these areas of robust increase or decrease, even the direction of projected precipitation change is inconsistent across the current generation of models. Indications are that the impacts on overall hydropower generation potential will be small, approximately +0.1% (Hamududu & Killingtvelt, 2012). Impacts on an individual project, a river basin or a region could, however, be quite substantial and detailed assessments would need to be undertaken.

Hydropower should be part of strategies to adapt to climate change, particularly as reservoirs provide flexibility in freshwater supply for all purposes.

Economics

Costs

Capital expenditures

The main capital expenditures in hydropower projects include the costs of civil engineering works (dams, tunneling, powerhouse), electro-mechanical equipment, access roads, transmission lines, and related engineering, procurement and construction management expenditures. Also to be included are the costs of planning, feasibility assessment, permits, environmental impact analysis, mitigation of impacts, resettlement and maintaining water quality.

Costs are very project specific. The ratio of electro-mechanical equipment to civil works is usually high for small projects, low-head and RoR developments; for larger reservoirs, civil engineering works dominate the overall bill. Capital expenditures relative to civil works also vary considerably, depending on the type of project, difficulty of access, labour costs and commodity prices for cement and steel, all of which are country and region dependent. By contrast, the costs of electro-mechanical equipment follow world market prices.

There is a wealth of cost studies on HPP, providing a range from as low as USD 1 050/kW to as high as USD 7 650/kW for large projects, and between USD 1 300/kW and USD 8 000/kW for smaller projects (IRENA 2012). As a comparison, refurbishment and upgrade usually cost between USD 500/kW and USD 1 000/kW.

Project costs for PSP are also very site-specific. Some quoted costs vary from USD 500/kW to USD 2 000/kW (Lempérière, 2008). The average cost of current projects in Europe is estimated at EUR 961/kW (USD 1 200/kW) (Steffen, 2012).

Other costs and levelised cost of electricity[6]

Operation and maintenance costs of hydropower, apart from major refurbishment or upgrade, are usually in the range of USD 2/MWh to USD 5/MWh, but costs up to USD 24.5/MWh have been reported in rare cases (IEA/NEA, 2010). Life expectancy and

6. Levelised cost: the total cost of building and operating a generating plant over its economic life, converted to equal annual payments.

Box 7: Sensitivity of LCOE to variations of capacity factor and cost of capital

The levelised cost of electricity (LCOE) from HPP is very sensitive to variations of plant capacity factor and the cost of capital used for financing, as shown on Table 6 for a development with a construction period of 5 years followed by a 50-year life span. The investment cost is assumed as USD 1 500/kW with operation and maintenance (O&M) costs of 2.5% of this amount.

Note that if one compares different options for the equipment of one single site, the reasoning will be different. Yearly production depends on the site characteristics, water flows and head. With sufficient reservoir capacity, the only differences in the various options may lie in the relative sizes of the electrical equipment: larger for a peaking plant, smaller for a base-load plant. Variations of the lcoe might be only +/-20%. Under fair time-of-use electricity pricing, the variation of revenues might be more important than that of costs.

Table 6: Variations of the LCOE of a representative hydropower plant with WACC and load factor

LCOE (USD/MWh)		***Weighted average capital cost or discount rate***		
		8%	10%	12%
Load factor	25%	90	110	133
	50%	41	51	61
	75%	28	34	41

costs of capital (weighted average capital costs, or discount rates in case of a purely public investment) are significantly more important for such large investments, as are lead times, and the perception of project risks by investors and lenders. These aspects are considered in more detail in the section on financing below.

The capacity factors of HPP vary widely, depending on the design and role for which they have been optimised. While RoR plant capacity factors depend mainly on the variations of the resource, reservoir HPP can be designed as base-load, mid-merit or peak plants. For base-load plants, the reservoir serves to dampen the resource variability; for peak plants, it also allows for the generation of electricity to be concentrated into the hours when it is the most valuable. An analysis of 142 HPP in the Kyoto Protocol's clean development mechanism (CDM) pipeline reveals that the average capacity factor of these projects is 50% – they run 4 380 hours equivalent full load per year; however, individual load factors range from 23% to 95% (Branche, 2011). Peaking plants have load factors much lower than average, as they are designed with much higher capacity (MW).

Large hydropower is largely competitive with other electricity sources, with lcoe as low as USD 20/MWh in best cases (low cost, high capacity factor projects) (Table 7). Derived from analyses of the CDM project database maintained by UNEP Risoe Center, Bloomberg New Energy Finance recently estimated the levelised cost of electricity (LCOE) of larger HPP at USD 67/MWh on average, though it can be as low as USD 25/MWh, and as high as USD 180/MWh (high cost, low capacity factor projects). Smaller projects may have roughly the same average levelised cost of electricity, but some go as high as USD 227/MWh (BNEF, 2012). IRENA (2012) provides for similar ranges of values but adds that very small projects can have LCOE of USD 270/MWh "or more for pico-hydro projects". Large differences across different countries are observed.

Table 7. Minimum and maximum LCOE for selected electricity generating technologies

Technology	Bioenergy	Bioenergy co-firing	Geothermal	Solar PV	CSP	Hydro	Wind onshore	Wind offshore	New coal	New gas CCGT	Micro hydro	Small-scale Solar PV	Small-scale Biogas
min USD/ MWh	80	80	35	155	160	**20**	50	140	40	40	**35**	185	110
max USD/ MWh	250	140	200	350	300	**230**	140	300	90	120	**230**	600	155

Source: IEA, 2012b.

Costs *vs.* benefits

Economic analyses are used for multi-purpose developments to better understand the value of the benefits provided. Governments, agencies and regulators need to understand the economic parameters for any hydro project they are considering.

In many regions and markets, some energy and most water management services are provided without compensation or an understanding of their value. IEA Hydro has started a new research project on hydropower services to evaluate the costs and benefits of the following aspects:

- integration of any non-firm renewable resource, such as wind energy, solar energy, biomass, etc., that is both large scale and subject to rapid fluctuations in supply;
- the provision and sale of ancillary services by hydropower producers;

- requirements for hydropower plant equipment and its controls, modifications and decision-support software, to enable rapid integration;
- the provision of water management services; and
- socio-economic impacts of hydropower development.

Hydropower is the only large-scale, cost-efficient storage technology available to support electrical systems. Conventional reservoir hydro projects are even less costly than pumped storage plants (Eurelectric, 2011).

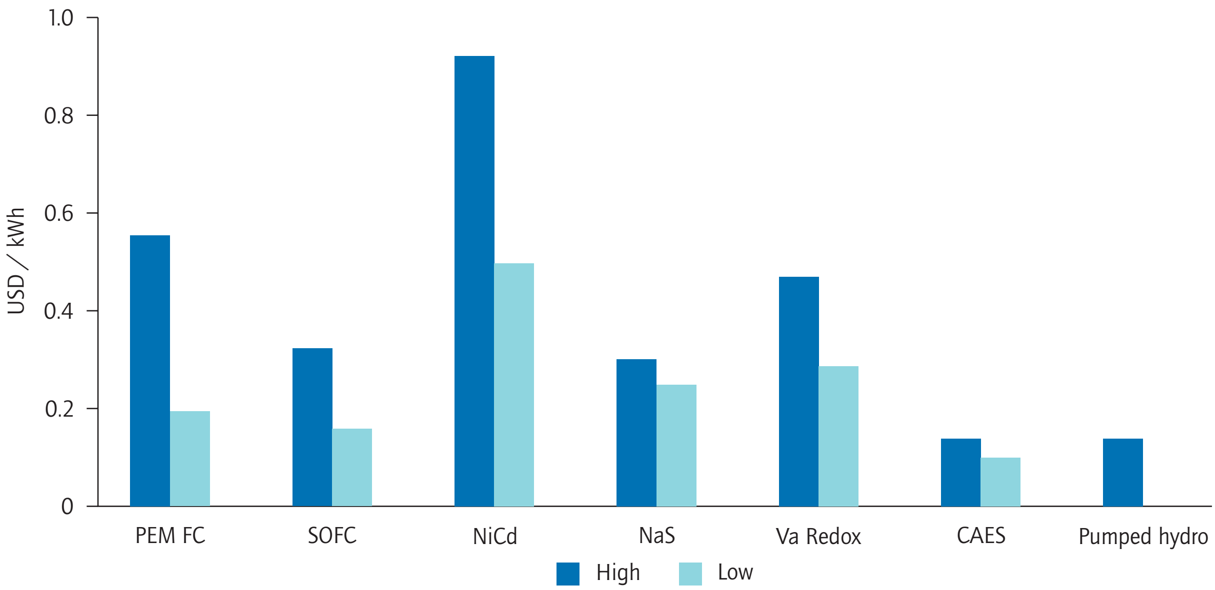
Economics of pumped storage hydropower

Existing PSP get most revenues from the difference between peak and off-peak prices – the price at which owners sell energy, and the price at which they bought it. For a project to be viable, these revenues, minus efficiency losses and possible grid fees, must cover investment, operation and maintenance costs. The spread between peak and off-peak prices has diminished in various areas, including those where the need for storage is increasingly recognised, such as Europe and the United States.

In the United States, the main reason for this closing of the gap may be the low price of natural gas, driven down by the boom in shale gas and the wide availability of gas-fired plants. Although more than 16 GW of new PSP capacities have recently been licensed, only 1 GW will be commissioned by 2020, almost all of it through modernisation and upgrade of existing PSP (Fisher *et al.*, 2012).

In Europe, growing shares of renewable may have played a significant role due to the merit order effect that reduces electricity prices on spot markets, which are based on marginal running costs. For example, PSP plants in Germany have collected about kEUR 87/MW (kUSD 112) in 2008 but only kEUR 35/MW (kUSD 45) in 2010. Ancillary service markets – especially negative secondary reserve - may now provide greater revenues in Germany, with 83 kEUR/MW (kUSD 107) on average 2008-10 (Steffen, 2012). These various revenue streams are not cumulative, however, as the same MW cannot be fully devoted to arbitrage (buying/selling) and reserve at the same time.

Figure 15: Costs of electricity storage technologies



Note: PEM FC = Proton exchange membrane fuel cell; SOFC = Solid oxide fuel cell; NiCd = Nickel cadmium battery; NaS = Sodium-sulphur battery; Va Redox = Vanadium redox flow battery; CAES = Compressed air energy storage. For the high case the assumed price for electricity is USD 0.06 per kWh; for the low case USD 0.04/kWh.

Source: NREL, 2009.

The situation is paradoxical. The need for a significant development of electricity storage to support large-scale variable renewable expansion is usually recognised, especially in countries with limited hydropower potential. Pumped storage hydropower is the largest option available – and the cheapest (Figure 15). Nevertheless, its economics in the market seem to have weakened. One reason might be that the need is foreseen years in advance, while competitive markets reflect short-term values. The need for storage to accommodate variable renewables is still not fully valued by the markets. Restructured markets may also not reflect the true portfolio value of PSP, *i.e.* its contribution to the optimisation of the entire generation system.

In most countries, PSP operators have to pay grid fees, sometimes during both pumping and electricity generation. Generally, however, pumping takes place when the grid is far from being fully used, so the marginal cost of using it at those times is close to nil, contrary to fixed costs. Reconsidering grid fees in pumping mode and possibly waiving them, as did Germany in 2009 for new plants, may represent a pragmatic first step towards a fair valuation of storage. In the longer term, market designs need to evolve to ensure that storage and reservoir hydropower, as well as other means, are given the appropriate market value for their flexibility and develop fast enough to balance the rise of variable renewables while preserving energy security for all.

Support mechanisms

Governments in many countries willing to support the deployment of renewables have included some form of support for new hydropower projects, most often as direct payments or tax incentives. This is the case in more than 40 countries, including Brazil, Canada, China, India, Norway, Russia, Sweden and the United States – 8 of the top 10 producers. Some focus on encouraging upgrades and modernisation, though often limited to small-scale hydropower (whatever the definition of small is in a given incentive scheme). Public banks and international finance institutions help to finance many projects in developing countries.

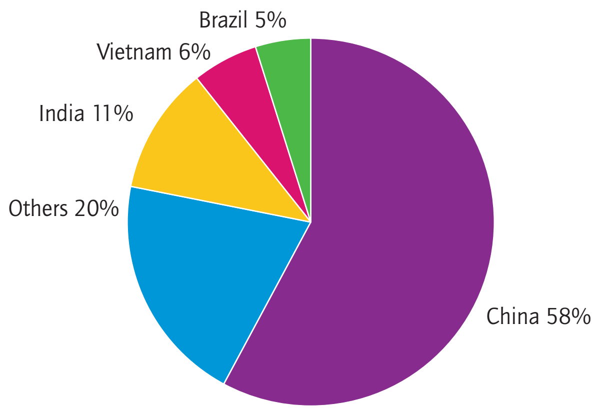
The focus should be on designing markets in a way that does not preclude investments that are profitable only over the long term; long-term power purchase agreements alleviate the uncertainty created by the price volatility of competing fossil-fired technologies, to the benefit of hydropower project developers, but also utilities and customers. In particular, market design should be further developed to value and reward not only energy, but all ancillary services and associated benefits. This will help enable the economic development of additional reservoir HPP and PSP to stabilise grids, ensure energy security and integrate larger shares of variable renewables.

Though proving difficult in the international negotiations on climate change, the introduction of a price on CO_2 emissions will appropriately differentiate HPP from fossil-fuelled alternatives. The scenarios of *ETP 2012* are consistent with implicit carbon prices of USD 40/tCO_2 by 2020, USD 90/tCO_2 by 2030, USD 120/tCO_2 by 2040 and USD 150/tCO_2 by 2050.

Clean development mechanism

From an international standpoint, one mechanism to value GHG emission reductions in developing countries is the clean development mechanism (CDM). Hydropower now leads the CDM, both in number of projects and in amounts of certified emission reductions (CERs). It is expected that approximately 330 million CERs will be issued from these projects by 2012, or about 15% or the total CERS to be issued by 2012 (AEA, 2011). Those CERS issued from 2008 to 2020 HPP in the CDM are expected to generate over 2.4 billion carbon offsets or 23% of all offsets from the CDM (CDM Watch, 2012). China alone generates 58% of these CERs, and Brazil, India and Vietnam together 22% (Figure 16).

Figure 16: Share of hydropower projects per host country



Sources: CDM Watch, 2012.

Given the scientific uncertainties concerning greenhouse gas emissions from reservoirs, a rough criterion was instituted to determine the eligibility of hydroelectric power plants for CDM project activities, based on the notion of power density (*i.e.* installed power generation capacity divided by the flooded surface area, in W/m^2). Hypothetically, two storage projects with similar power density would have the same emissions independent of climate zones or of inundated biomass and carbon fluxes. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) notes, however, that there is little link between installed capacity, the area of a reservoir and the various biogeochemical processes active in a reservoir. As such, the power density rule may inadvertently impede the development of socially-beneficial hydropower projects, while at the same time supporting less beneficial projects. On-going scientific work is expected to lead to more appropriate criteria. Even if the CDM provides only a small share of the overall revenues of HPP, it can increase investment profitability.

Financial challenges

Perhaps the biggest change in the way hydropower projects have been developed over the last two decades has been in their financing. Traditionally, hydropower development in most countries required public sector involvement; many existing hydropower facilities had total or partial public financing. Public funding for new hydropower projects has diminished substantially with the electricity industry evolving towards liberalisation, with private financing, operation and ownership. In some countries such as China, however, public companies continue to develop the project, provide the funds, undertake construction and manage operations. Chinese financial institutions are said to have outpaced the World Bank in financing hydropower projects worldwide.

Like most renewable energy technologies, hydropower is capital intensive, but has very low operating costs. Hydropower projects require long construction periods and large upfront capital costs. Returns on investment may vary greatly from year to year, with rain patterns. If this is coupled with a market-based, power-purchase model, the risk exposure may be considered untenable. With construction typically about 80% of total project costs and technical lifetime around 30 to 40 years for electro-mechanical equipment, and more than 80 years for civil works, project viability relies critically on long tenure, which is typically difficult to obtain from private commercial lenders.

With significant hydropower potential in developing nations, policy, price and political uncertainty are also concerns for potential investors, adding an additional level of complexity and risk to financing. The inability to provide project financing that meets the needs of both the developer and the lender is often the main challenge to the development of sustainable hydropower projects, particularly where public funds are scarce and private investors consider the risk is too high.

A possible solution to such an impasse is the public-private partnership (PPP), through which financial efforts, risks and returns are shared between private investors and the public sector, to provide the synergies for a positive outcome. A PPP can also be valuable in countries that lack sufficient financial resources and have utilities with shortages of technical skills. The public sector takes the lead in creating the appropriate institutional and legal framework, and partners with the private sector in development, as in the case of the Nam Theun 2 project (Box 8).

National public banks and international financial institutions (IFIs) play a crucial role in supporting the public sector in PPPs. As such, they are a catalyst for hydropower project development through:

- Setting an appropriate institutional and business framework. This involves supporting the public sector to create an attractive environment for private sector investment (*e.g.* mobilising grant assistance, initiating baseline studies, encouraging local capital market development and cross-border/regional opportunities, promoting understanding of hydropower sustainability).
- Preparing and developing projects alongside public and private players (*e.g.* helping to set up a realistic option assessment process, fund feasibility studies, simplify and standardise processes/documentation to make projects easier to close).
- Helping to resolve financial challenges (*e.g.* providing long-term loans appropriate for the infrastructure assets, lending more at a decentralised level, providing insurance and guarantees for risks that neither the private sector nor the government can handle, providing refinancing facilities to allow commercial banks to extend loan periods, mobilising international co-financing).

Box 8: Financing the Nam Theum 2 project

The Nam Theun 2 Hydroelectric Project (NT2) (see Box 3) is owned by private shareholders and the government of Laos PDR (GoL) and backed by commercial lenders and international financial institutions including the World Bank, the European investment bank (EIB) and the Asian Development Bank (ADB). Nam Theun 2 power company (NTPC) was formed by GoL and private shareholders to build and operate the project for the first 25 years.

The project had a total investment cost, including contingencies, of USD 1.3 billion, with the project financed on a debt-equity ratio of 72/28. The financing arrangements reflect project economics. The senior debt facilities in USD include political risk guarantees from the ADB, the World Bank and the multilateral investment guarantee agency (MIGA), export credit agency support and direct loans from a number of multilateral and bilateral development agencies. Nine international commercial banks and seven Thai commercial banks are providing long-term loans. Project financing was completed by shareholder contribution of equity pro-rata to their respective participation in NTPC. The Lao government's equity is financed by means of loans, grants and other financing from international institutions. About 85% of the total cost has been funded from the private sector.

The electricity generating authority of Thailand (EGAT) is contracted to purchase power from NT2 at an agreed tariff on a take-or-pay basis for the duration of the 25-year operating concession and therefore assumes market risks. Under a similar agreement EDL (the Lao electricity utility) undertakes to buy energy at an agreed tariff on a take-or-pay basis.

The hydrological risk is shared between EGAT and NTPC. Construction risk was borne by the head contractor, which in turn passed on a substantial portion of that risk to the five subcontractors under fixed price contracts with heavy penalties for late delivery. Thai political risk associated with the off-take agreement is reduced by the involvement of the Thai commercial lenders, while the international debt is backed by various multilateral development banks and export credit agencies. Government obligations under the Concession Agreement are backed by the World Bank and ADB.

The increasing role of the private sector in hydropower development has created some challenges:

- With large hydropower in public sector ownership, government policy was to keep tariffs low, partly to support local economic development. In the private ownership model, developers and financiers require commercial rates of return, and governments seek revenue from royalties, taxes, etc.. This has increased the production cost of hydropower.
- A privately financed hydropower project will be sized to deliver maximum commercial returns, whereas the same project developed with public funding would likely be sized to maximise the use of the water resource, including multi-purpose benefits. Where international financial institutions (IFIs) are involved, some provision of non-energy benefits is usually required.
- Long repayment periods are decisive for the financial viability of a hydro project. Loan maturities average 5 to 10 years for commercial banks, 10 years for corporate bonds and 10 to 25 years for IFI loans – all of which are shorter than the normal economic life (50 to 80 years) of a hydropower project.

Project risks and mitigation

In order for investors and lenders to be willing to engage in the funding of a hydropower project, it is essential that all risks be properly identified, quantified where possible, effort be made to reduce them, and residual risks be properly allocated, managed or mitigated among the various stakeholders.

With no two hydropower projects being the same, it is not possible to use a standardised financial framework. However, setting a common basis for risk identification and mitigation measures helps

Box 9: Auction procedures in Brazil and the role of the BNDES bank

The Brazilian power sector model initiated in 2004 relies on a combination of planning and competition (with both private and government-owned companies) to guarantee supply adequacy and provide a relatively predictable environment for attracting new investors. The model states that the energy distribution companies should acquire their energy supply through public auction.

For the distribution companies, the purpose of such auctions is to contract power to fully meet their forecast demand (three to five years in advance). Before the auction, each distribution company indicates the amount of energy it will need. The individual energy demands are then aggregated to a single pool, which will purchase the sum of the amounts requested by all distribution companies.

During the auctions, the generation projects are sorted in ascending order, according to the bid price offered by the developers of the project, until their aggregated supply fully meets the pool energy demand. The developers that offer the biggest discounts on the price cap are declared winners and then contracted with all distribution companies.

For power distributors, this mechanism socialises the gains of trade, for example, ensuring that all distributors may face exactly the same hiring costs per unit of energy. For power generators, this mechanism reduces the risk of default since they sign a power purchase agreement with all distribution companies. Auctions also represent an opportunity of selling their energy by long-term future contracts, even before the construction of the power plant. This implies a reduction of risks and uncertainties, and also contributes to lowering the costs of electricity generation.

In the particular case of hydropower generation projects, due to the amounts of money involved in the development phase and the long time needed for their construction, credit lines with specific conditions may be necessary.

Brazil's BNDES (National Bank for Economic and Social Development) has been the leading provider of long-term financing for infrastructure investments. For the Brazilian electricity sector, BNDES support involves financing investment projects and equipment acquisition, thus allowing the execution of projects with high investment volumes and long-term deployment period. From January 2003 to June 2008, the bank supported 142 power generation projects totalling about BRL 21.3 billion (USD 10.5 bn) in financing, of which BRL 13.6 billion (USD 6.7 bn) went to hydroelectric projects.

improve financial success. Such mitigation may include considering smaller hydro installations which may not be the optimal but may be more attainable. Depending on the nature of the project, the main risks potentially affecting hydro plant financing may include:

- construction risk;
- hydrologic risk;
- off-taker risk;
- regulatory risk; and
- life-cycle risk.

Construction risk

Construction costs represent up to 80% of hydropower project development costs, so any cost overruns or schedule delays can have a significant impact on project finance. The main issues that can increase construction risk exposure include geological conditions, scope changes in design and technology, and poor execution of the construction contract.

Established approaches to managing construction risk include extensive site investigations and design studies, together with effective preparation and management of contracts. The significant use of local workers during the construction phase, with funding provided in local currency, minimises exchange rate risks. More recently, risk has been managed through innovative contractual methods, such as the engineering, procurement and construction (EPC) contracts with a credit-worthy and experienced organisation. Such a contract may stipulate a fixed price with penalty clauses, thereby allocating construction risk to the contractor. This type of contract normally results in a higher, albeit less risky, cost to the developer.

Hydrologic risk

Establishing accurate hydrologic data during the study phase of a development is fundamental to estimating power output, as well as design of spillways and other flood discharge works. Hydrologic variability and inaccuracy can be problematic in a privately financed project with power purchase agreement (PPA)[7] obligations, and could affect the stable revenues needed to service debt obligations. This is an important risk factor in developing regions where many large rivers with significant hydro potential have little if any reliable, historic flow data.

One approach to mitigate the risks of lower power output – and hence revenue – arising from reductions in river flow and reservoir level, is through a flexible PPA. The hydrologic risk can be shared with the power off-taker, which is often better able to withstand this risk exposure through access to multiple generating sources. If the risk is still too great, lenders may require additional guarantees.

7. A contract between seller and buyer of electricity, which specifies all key parameters such as timing, schedules, payment, penalties and termination.

Off-taker risk

In emerging markets, power sector operators are interested in hydropower development if asset-based revenues can be assured. Similarly, lenders look for stable revenue streams to ensure financial obligations will be met. To mitigate the risk of non-payment, hydropower projects mainly use a long-term PPA with a credit-worthy off-taker for the capacity and energy output. At the same time, the project has to provide the buyer or off-taker with a dependable supply. In addition, the PPA could include provisions for adjustments to changes in exchange rate and inflation.

Regulatory risk

The stability of the regulatory and institutional framework, including permit processes, is the most important factor in financing energy infrastructure projects. Regulatory issues include:

- the rules of the electricity market where the project will operate;
- the track record of the regulating agency;
- mechanisms in place for tariff adjustments;
- changes in the law and the financial equilibrium of the concession;
- changes in the tax system; and
- predictability of policy framework.

Regulatory risks are difficult to mitigate within the project structure and lenders need to carefully study and assess whether the regulatory framework lends itself to prudent decision-making. Some hydropower projects may be exposed to regulatory risk that can result in high financing costs.

Life-cycle risk

Project risk extends into the operating phase of the hydropower plant, as ongoing safety, dependability and environmental compliance are fundamental to the long-term financial performance of the project. Compliance starts with the design and construction phase, and continues through appropriate levels of maintenance and refurbishments, as required, for the life of the plant. The most significant issues include dam safety, equipment dependability and compliance with environmental regulations.

Technology improvements: roadmap actions and milestones

While hydropower is the most efficient power generation technology, with high energy payback ratio and conversion efficiency, there are still many areas where small but important improvements in technological development are needed. Work is underway to identify and apply new technologies, systems, approaches and innovations, including experience from other industries, that have the potential to make hydropower development more reliable, efficient, valuable and safe. Improvements along the lines of those made in the last 30 to 50 years will also continue, though with smaller incremental benefits: mainly in physical size, hydraulic efficiency and environmental performance.

Technical improvements

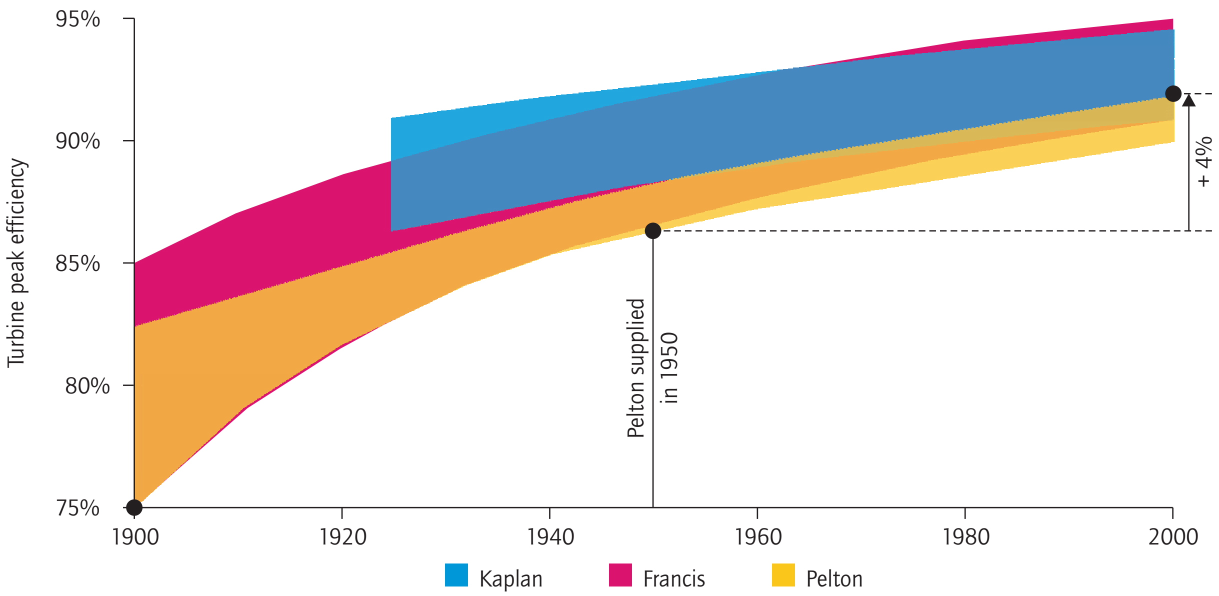
Technology	Timing
Further improve turbine efficiency and environmental performance	2012-50
Develop roller-compacted concrete (RCC) dams	2012-30
Develop low-head and kinetic flow turbines for use in canals, pipes and rivers	2012-30

Improvements in turbines

The hydraulic efficiency of hydropower turbines has shown a gradual increase over the years: modern equipment reaches 90% to 95% (Figure 17). This is the case for both new turbines and the replacement of existing turbines (subject to physical limitations). Computational fluid dynamics (CFD) has facilitated detailed examination of the characteristics of fluid flow and optimisation of runner design. These continuous improvements in turbine technology have been driven by the requirements for:

- increased power output and improved efficiency;
- greater flexibility in unit operation to suit market needs;
- increased availability and lower maintenance costs (reducing repair requirements caused by cavitation, cracking and sediment abrasion); and
- enhanced environmental performance: improving fish survival rates, allowing small flows to be handled efficiently for riparian flow issues and maintaining acceptable water quality standards.

Figure 17: Improvement of hydraulic performance over time



Source: Stepan, 2011.

Some improvements aim directly at reducing the environmental impacts of hydropower. Fish-friendly turbines have been mentioned earlier. Aerating turbines use the low pressures created by flows through the turbines to induce additional air flow. This increases the proportion of dissolved oxygen, protecting aquatic habitat in waters below dams (March, 2011). Oil-free turbines use oil-free hubs and water-lubricated bearings to eliminate the possibility of oil leakage to the river. Other benefits include easy maintenance and lower friction than with the oil-filled hubs.

Continuous improvements in material properties have been driven by requirements to:

- improve resistance to cavitation, corrosion and abrasion to extend component life and reduce outages;
- reduce runner weight and improve efficiency through increased strength of materials; and
- improve machinability to increase power output as more complex shapes can be manufactured.

This has led to increased use of proven and new materials such as stainless steel and corrosion- or abrasion-resistant coatings in turbines, and lower cost or higher performance fiberglass or plastic materials in construction.

Hydrokinetic turbines

In-stream flow turbines, sometimes referred to as hydrokinetic turbines, rely primarily on the conversion of energy from free-flowing water, rather than from hydraulic head created by dams or control structures. The recent surge of research activity and investment in technology to capture tidal energy has already produced successful prototypes. Most of these underwater devices have horizontal axis turbines, with fixed or variable pitch blades. Electrical generators tend to be direct or hydraulic drive, or have rim-mounted stators.

Improvements in civil works

The cost of civil works associated with new hydropower project construction can be up to 70% of the total project cost, so improved methods, technologies and materials for planning, design and construction have considerable potential (ICOLD, 2011a). A roller-compacted concrete (RCC) dam is built using much drier concrete than traditional concrete gravity dams, allowing speedier and lower cost construction. Trapezoidal cemented sand and gravel (CSG) dams (*e.g.* in Japan) use more local materials, reducing costs and environmental impact. Recent improvements in tunneling technology have reduced costs, particularly for small projects.

Managerial improvements

Managerial improvements	***Timing***
Upgrade or redevelop old plants to increase efficiency and environmental performance	2012-50
Add HPP units to existing dams or water flows	2012-30

The vision for this Hydropower Roadmap is to develop significant increases in energy and capacity, with most of this to be derived from new hydropower developments. However, the first priority should be managing existing hydropower developments to both ensure their capacity is maintained over the long term, and gain any feasible increases in output of energy and services. It is also important to consider any opportunities to add hydro capacity to existing water resource facilities that do not have power generation.

Hydro plant machinery deteriorates with age and will eventually fail, principally due to thermal, electrical and mechanical degradation of insulation materials used in the windings and elsewhere, and erosion, corrosion and hence fatigue in turbine components. The capacity of HPP will decrease as equipment, and waterways and reservoirs get progressively clogged with silt, operating costs exceed revenues or generation ceases due to a major component failure. Regular maintenance and replacement of damaged or obsolete equipment is needed to maintain the original level of service. Upgrades may include modifications to reduce environmental impacts through the introduction of fish-friendly turbines, or improving safety to cope with exceptional floods or earthquakes.

Asset management of hydroplants

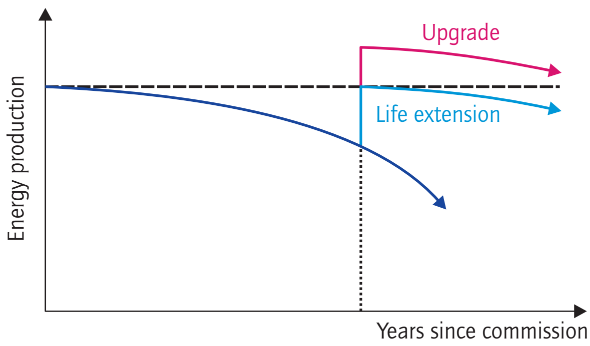
Throughout the world, many existing hydro projects have been in operation for a long time and some perform far below either their original capability or their potential. To determine how best to maximise their long-term value is often termed "asset management" (Nielsen and Blaikie, 2010).

Asset management aims to effectively maintain or even improve the asset capability to the required level of service (LOS) at the minimum cost of service (COS) over the entire project life cycle. In a business context, consideration across a portfolio of assets is termed strategic asset planning: many utilities and power companies develop a multi-year strategic asset planning framework, with appropriate operational and capital budgets.

If the assessment of an existing hydro plant indicates that the condition, performance or risk profile is less than acceptable, decisions have to be made on the most appropriate course of action. Experts distinguish three options: repair, rehabilitation or maintenance, where components are replaced to their original status; modernisation, upgrading or uprating, providing improved performance and output; and redevelopment, which may include new powerhouses, equipment and structures (Stepan, 2011).

Life extension offers many opportunities for upgrading, as schematically suggested on Figure 18.

Figure 18: Evolution of production over time



Source: Lier, 2011.

Modernisation

When a hydro plant reaches the age of 30 to 40 years, it should be screened for possible improvements in the equipment and components. Advances in technology have meant that the performances of many hydro plants can be improved, particularly in turbine efficiency. In addition, if additional discharge is available and if the structures allow it, increased output can be considered.

A number of developments are driving the need for such improvements. Changes in the electricity market have meant that in many jurisdictions there is a need to provide more flexible operation. Increasing application of variable renewable energy has created even greater demands on the energy services provided by hydropower units, particularly the case for pumped storage plants.

In many situations, modernisation or upgrading of older hydropower projects can be more cost-effective than building new projects, have relatively smaller environmental and social impacts, and be faster to implement. Replacement of equipment (such as turbine runners, generator windings, excitation systems, governors and control panels) can increase efficiency, improve reliability and provide greater flexibility as well as reducing operating costs.

Overall, the potential for improvements in output may be between 10% and 30% in hydroplants that have not already been upgraded. A 4% to 8% increase in efficiency is held to provide financial justification for upgrading turbines (see Figures 17 and 18). A general description of potential technological improvements may be found in EPRI (2006).

Redevelopment

Careful analysis sometimes suggests that an existing hydro plant should be replaced. This may be because the plant is very old, the equipment is obsolete or the refurbishment costs are too high. It may also be because only a small power plant was needed originally, but a much larger hydro plant is now possible, and needed. Triggers suggesting redevelopment may be feasible include:

- very old (≥40 years) and obsolete equipment;
- high operational and maintenance costs;
- safety and security concerns;
- no longer meeting relevant regulations; and

- opportunity to bypass one or more older power plants with a new development having a greater hydraulic head and power output.

There are many sites where the redevelopment of an old hydro plant has resulted in significantly greater output with very few environmental and social impacts.

Adding hydropower to existing water resource projects

Most of the world's 45 000 large dams were built to control floods; to store and divert water for agriculture, irrigation and urban water supply schemes; or to provide reservoirs for navigation, fisheries and recreation. Only about 25% of these large dams include the provision of hydropower generation, and only around 12% to 13% of all dams globally have hydropower as their main purpose (ICOLD, 2011b). A combination of market changes and technical improvements would justify retrofitting of hydropower generation to some older dam structures in every region of the world.

In addition, hydropower generation could be fitted to other existing water resource structures, such as barrages, weirs, canals and other water conduits. These often have very low hydraulic head, so require the use of specific low head (or in-stream flow) technologies. There are also opportunities to retrofit water supply and waste water schemes that have significant hydraulic head.

Innovations in pumped storage hydropower technologies

Pumped storage improvements	*Timing*
Use variable-speed pump turbines for PSP projects to provide greater variability	2012-20
Develop seawater PSP in conjunction with offshore resources (wind power, marine power)	2020-50

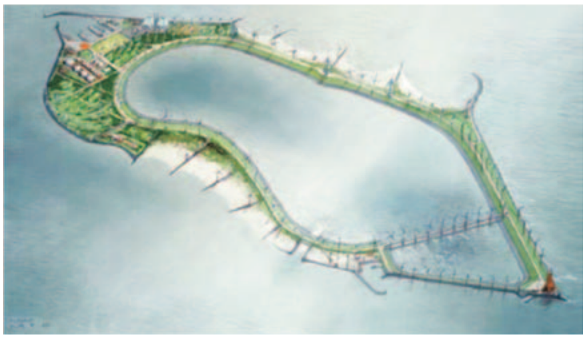
Under normal operating conditions, hydropower turbines are optimised for an operating point defined by speed, head and discharge. At fixed-speed operation, any head or discharge deviation involves some decrease in efficiency. Variable-speed pump-turbine units operate over a wide range of head and flow, improving their economics for pumped storage. Furthermore, variable-speed units accommodate load variations and provide frequency regulation in pumping mode (which fixed-speed reversible pump-turbines provide only in generation mode). The variable unit continues to function even at lower energy levels, ensuring a steady refilling of the reservoir while helping to stabilise the network. Wear and tear on the machine, seals and bearings is reduced.

For very flexible operations, so-called "ternary pump turbine units" group separate pump and turbine on a single shaft with a unique motor/ generator. These units operate in a single rotational direction allowing for rapid transitions from power absorption to power production and back.

The first marine pumped storage system was developed in 1999 on the Japanese Island of Okinawa, with seawater as the lower reservoir and a man-made reservoir on top of cliffs as the upper reservoir. Running turbines with seawater is a proven, mature technology – the tidal plant of La Rance in France has been operating for almost 50 years. Much larger projects are under consideration in various parts of the world. For example, in France, various GW-sized plants could be installed in Normandy and Brittany, where the variable wind resource is good (Lemperière, 2011). Each would require about 1 km^2 of land.

It has also been proposed to create entirely artificial seawater or freshwater PSP systems in the absence of natural declivity. A Dutch company, Kema, has further developed the concept of "Energy Island" to build off the Dutch coast in the North Sea. It would be a ring dyke enclosing an area 10 km long and 6 km wide (Figure 19). The water level in the inner lake would be 32 metres to 40 metres below sea level. Water would be pumped out when electricity is inexpensive, and generated through a turbine when it is expensive. The storage potential would be 1 500 MW by 12 hours, or 18 GWh. It would also be possible to install wind turbines on the dykes, so reducing the cost of offshore wind close to that of onshore, but still with offshore load factors.

Figure 19: Concept of an energy island



Source: Kema, 2007.

Similarly, in the absence of favourable geographical relief it is conceivable to create fully artificial reservoirs on flat land. The costs would however be more significant. In Germany, RAG, the company that exploited coal mines, is considering creating artificial lakes on top of slag heaps or pouring water into vertical mine shafts, as two different new concepts for PSP (Buchan, 2012).

Policy framework: roadmap actions and milestones

This roadmap anticipates a doubling of hydropower by 2050, mostly in Asia, Africa and South America, driven by the search for energy security, environmental sustainability and promotion of social and economical development, especially for local communities. Actions necessary to achieve this target relate to the policy framework, sustainability and public acceptance, and economic and financial challenges.

Setting up/improving the policy framework

This roadmap recommends the following actions	***Timing***
Prepare national hydropower inventories	2012-20
Consider HPP in the option assessment for each country's energy and water resource planning activities	2012-20
Integrate HPP development in energy and water planning at river basin level	2012-20
Develop international co-ordination of hydropower development when river basins cross borders	2012-20
Set targets for hydropower development, including upgrade and redevelopment of old HPP and additions to existing dams and waterways	2012-20
Streamline permit processes while maintaining the highest level of sustainability requirements	2012-20
Update and adjust hydropower targets	2020-50
Acknowledge HPP and PSP as enablers of variable renewables	2020-50
Where necessary, consider increasing electric capacities of existing reservoir HPP and PSP to better enable the development of variable renewables	2020-50

Each nation with hydropower potential should prepare or update its inventory of hydropower potential (run-of-river, reservoir storage and pumped storage) in terms of technical, economic, environmental and social feasibility. This inventory should cover site selection, *i.e.*, the formulation of alternatives for the partition of the total water head of a river basin, by carefully addressing environmental, social and economic impacts and the benefits of the new projects, including multi-purpose development and all potential users of the water resource at river basin level.

This inventory should also take in account all opportunities to rehabilitate, upgrade or uprate existing HPP to increase efficiency; improve output, capacity and value; and enhance environmental performance.It is also important to consider any opportunity to add hydro capacity to existing water resource projects that presently do not already have it. HPP owners and operators should be at the forefront in identifying such opportunities, but public agencies could identify dams without generating facilities and assess their feasibility for hydropower.

Hydropower should be included in the option assessment for each country's energy resources, considering both short-term operational and long-term expansion planning. Targets for hydropower should be developed, taking into account all concerns and any cross-boundary issues, for integration with the national strategic energy plan. Environmental permits should include an environmental impact assessment (EIA) that encompasses social issues and water use rights. In this process, hydropower should be treated equally with all other sources of renewable energy and included in all analyses and discussions. The potential of reservoir HPP and PSP to help integrate variable renewables such as wind power and PV electricity should be acknowledged. As these renewable energy technologies are being deployed, the potential for increasing the electrical capacities of existing reservoir HPP and PSP should also be considered.

The progress of hydropower development in each nation should be tracked and included in an international database.

In areas with low rates of electrification, smaller-scale hydropower development should be encouraged due to the associated benefits in improving electricity and freshwater supply.

Existing hydropower developments should be managed to ensure their capacity is maintained over the long term, and to achieve feasible increases in output of energy and services. (Rehabilitation is usually cheaper than developing new capacity.)

Ensuring sustainable development and gaining public acceptance

This roadmap recommends the following actions	***Timing***
Consider sustainability criteria at river basin level	2012-20
Document approaches to sustainability (including protocols or guidelines); developers should regularly report on levels of achievement	2012-30
Avoid, minimise, mitigate or compensate negative socio-economic and environmental impacts	2012-30
Develop tools to monitor and manage GHG emissions from reservoir HPP	2012-50
Consider positive impacts of HPP development	2012-30
Consider sustainability issues in the co-ordinated operation of hydropower plants	2012-20
Disseminate information on the roles of hydropower in combating and adapting to climate change	2012-50
Communicate with stakeholders at all stages of HPP and PSP development	2012-50

One of the most important stages in the sustainable development of hydropower is the selection of water head partition, carried out in the river basin inventory studies. The hydroelectric inventory is of paramount importance once the decision is taken not only for a single project but for the whole set of projects that can be developed in a river basin. Sustainability criteria should be utilised in this phase, requiring the development of methodologies that provide clear direction on how to minimise negative social and environmental impacts while maximising the positive ones and also capturing synergies between hydropower development and the river basin water resources.

All possible impacts of hydropower development must be considered and taken in account by developers and regulatory authorities. To the greatest possible extent, negative impacts should be avoided, both during the development and implementation of hydropower projects, and during their operational life cycle. Those that cannot be avoided should be minimised, mitigated or compensated. This includes environmental impacts (notably on water quality, wildlife and biodiversity), as well as socio-economic impacts on local populations. Developers should use guidelines or protocols reflecting recognised standards, and regularly report on their achievements in meeting sustainability objectives.

The positive impacts for sustainable development must also be considered, especially in comparison with possible alternative water and energy management options, as well as in promoting social improvements and regional development. Assessment of costs and benefits, including environmental aspects, should be clearly and widely communicated.

In terms of sustainability, the operation of the hydropower plant should consider the co-ordinated operation with upstream and downstream hydropower plants in the same river basin as well as the operation of the other power plants in the interconnected electrical power system. For example, the integrated operation can provide gains in energy production by taking into account hydrological synergies among river basins. The operation of hydropower plants should also consider other water uses in the river basin.

Finally, developers should keep stakeholders and all others with an interest informed in a direct and timely way. Stakeholder involvement is crucial to public acceptance.

Overcoming economic and financial challenges

This roadmap recommends the following actions	***Timing***
Reform electricity markets to ensure the adequate long-term revenue flows	2012-20
Place appropriate value on ancillary services and flexible capacities	2012-30
Value non-energy services from HPP development	2012-30
Ensure that financial decision making for sustainable projects takes full account of economics, environmental/social aspects and the long-term contractual framework	2012-50
Promote public and private acceptance of hydropower	2012-30
Ensure governments treat hydropower development as a key strategic choice and include its financing in policy agendas	2012-20
Develop effective financial models to support the large number of appropriately sized hydro projects needed in developing regions;	2012-50
Develop new risk-mitigating public financial instruments	2012-50
Reconsider grid fees for PSP in pumping mode	2012-20

With the electricity industry evolving towards deregulation in many countries, public funding for new hydropower projects has diminished substantially in favour of private financing, operation and ownership. Like most renewable energy technologies, hydropower is a capital-intensive business. Hydropower projects require long construction periods and large upfront capital costs.

One of the most pressing priorities in the hydropower sector is to develop the business model and financial instruments that will enable the required rapid growth in large-scale hydropower. The various risks for developers – from variations in rain patterns to uncertainties about future electricity prices – must be mitigated. In emerging economies the national public banking institutions, and in developing countries the international financing institutions, must enter into arrangements with the private banking sector to reduce the cost of capital and the level of risk.

Hydropower can make a considerable contribution to energy security in the context of decarbonising the energy mix, but this is likely to require the development of adequate financing schemes.

In countries restructuring their electricity markets, utilities could be induced to offer long-term power-purchase agreements to HPP developers, and markets to effectively reward flexibility in all aspects (demand-side management, interconnection, flexible generation and storage). The creation or strengthening of ancillary services markets could be part of this exercise.

The timing of investment in complementary technologies also needs attention. While policy makers plan to further deploy renewable electricity-generating technologies, they should be aware that onshore wind power or photovoltaic power plants have significantly shorter lead times than the reservoir HPP or PSP that could be necessary to balance the additional variability on electric grids.

Most importantly, the short-term market effects of renewables might be to depress electricity prices on spot markets and reduce the gap between peak- and base-load prices, thereby undermining the business model of PSP and, to a lesser extent, of reservoir HPP projects. This implies that market design reforms and renewable energy planning must be implemented in parallel and consistent manner.

Conclusion: near-term actions for stakeholders

This roadmap has responded to requests from the G8 and other governments for detailed analysis of the sustainable growth of hydropower, a key technology to mitigate climate change. It lays out a pathway, based on sustainable development, multi-purpose uses of the water resource, technology development and policies, to achieve the reductions in GHG emissions required by 2050. The IEA, together with governments, industry and NGO stakeholders, will report regularly on the progress made towards achieving the vision. For more information about the roadmap's actions and implementation, visit www.iea.org/roadmaps.

Stakeholder	Action items
National and local governments	• Include hydropower in energy and water planning. • Establish national inventories of hydropower potential. • Prepare development plans with targets for hydropower. • Reform electricity markets to ensure sufficient investment in flexible capacities, appropriately valuing hydropower energy storage and other ancillary services. • Attribute due value to non-energy contributions of multi-purpose hydropower developments. • Progressively remove subsidies to fossil fuels. • Introduce carbon pricing as an additional means to support hydropower's GHG performance. • Treat hydropower development as a strategic choice and include its financing in governments' policy agendas. • Invest in promoting public and private acceptance of hydropower. • Promote policy framework covering the development of sustainable and appropriate hydropower projects that avoid, minimise, mitigate or compensate any legitimate and important environmental and social concerns. • Streamline administrative processes to reduce the lead times for hydropower projects. • Develop new risk-mitigating public financial instruments. • Encourage national and international development banks to engage in hydropower development. • Enter into arrangements with the private banking sector to reduce the cost of capital and the level of risk.
Industry	• Document the approach to sustainability that will be followed during project development. • Consider rehabilitation, upgrading or redevelopment of existing HPP. • Assess the feasibility of adding HPP units to existing dams. • Adopt cutting-edge technologies with respect to efficiency and environmental performance. • Manage sedimentation in reservoirs. • Develop tools to monitor and manage GHG emissions from reservoirs. • Develop technologies to better support the integration of large shares of variable renewable energy sources. • Consider sustainability issues in the co-ordinated operation of hydropower plants.

Universities and other research institution	• Increase levels of education and training in all aspects of hydropower design, development and operation. • Support young engineers. • Understand the impacts of climate change on water resources and hydropower output, as well as any impacts on long-term climate change emanating from projects.
Non-governmental organisations	• Monitor progress towards sustainable hydropower development and policy milestones, and publish results to keep governments and industry on track. • Provide objective information on the potential of sustainable hydropower to mitigate climate change and increase energy security.
Intergovernmental organisations and multilateral development agencies	• Provide capacity building for regulatory frameworks and business models to help developing countries implement sustainable hydropower development.

Acronyms and abbreviations

CDM: Clean Development Mechanism

CER: certified emission reduction

CH_4: methane

CO_2: carbon dioxide

COS: cost of service

EIA: environmental impact assessment

EPC: engineering, procurement and construction

GHG: greenhouse gas(es)

GW: gigawatt (bn W)

HPP: hydropower plant

HVDC: high-voltage direct-current

IEA: International Energy Agency

IFI: international financial institution

IHA: International Hydropower Association

IPP: independent power producer

LCA: life-cycle analysis

LCOE: levelised cost of electricity

LP: Previous License (preliminary environmental license in Brazil)

LOS: level of service

MME: (Brazil's) Ministry of Mines and Energy

n.a.: Non available

OECD: Organisation for Economic Co-operation and Development

O&M: operation and maintenance

NGO: non-governmental organisation

PPA: power purchase agreement

PSP: pumped storage plant (or project)

PV: photovoltaic

RoR: run-of-river

SEA: strategic environmental assessment

TWh: terawatthour (1 TWh = 1 bn KWh)

WACC: weighted average capital cost

WWF: World Wide Fund for Nature

Detailed potential estimate in South and Central America

South America				
Country	**Reference year**	**Hydropower potential (MW)**	**Installed capacity (MW)**	**% of potential**
Argentina	2007	40 400	9 934	25%
Bolivia	2006	1 379	484	35%
Brazil	2010	260 093	80 703	31%
Colombia	2007	96 000	9 407	10%
Equator	2008	30 865	2 064	7%
Guyana	2010	7 600	n.a.	
Paraguay	2003	12 516	8 350	67%
Peru	2006	58 937	3 067	5%
Suriname	1994	2 420	n.a.	
Uruguay	2006	58 937	3 067	5%
Venezuela	2002	46 000	28 725	62%
Sub-total		**583 181**	**149 227**	**26%**
Central America and Caribbean				
Country	**Reference year**	**Hydropower potential (MW)**	**Installed capacity (MW)**	**% of potential**
Costa Rica	2008	66 333	5 013	76%
Cuba	2002	650	43	7%
Dominican Republic	2010	2 095	472	23%
El Salvador	1995	2 165	486	22%
Guatemala	2008	5 000	786	16%
Haiti	2009	137	65	47%
Honduras	2006	5 000	520	10%
Jamaica	2009	24	23	98%
Mexico	2005	53 000	11 619	22%
Nicaragua	2008	1 767	109	6%
Panama	2010	3 282	1 106	34%
Subtotal		**79 753**	**20 242**	**25%**

Sources: communication from OLADE and CEPEL.

References

AEA (2011), Study on the Integrity of the Clean Development Mechanism (CDM), EC DG Environment and Climate Action, http://ec.europa.eu/clima/policies/ets/linking/docs/final_report_en.pdf retrieved 1 August 2012.

Altinbilek, D. *et al*. (2001), "Hydropower's Contribution to Energy Security", *World Energy Congress, Rome.*

Bloomberg New Energy Finance (BNEF) (2012), *Q2 2012 Levelised Cost of Electricity Update*, 4 April.

Bonnelle, D. (2012), personal communication.

Branche, E. (2011), "Hydropower: the strongest performer in the CDM process, reflecting high quality of hydro in comparison to other renewable energy sources", Paper presented at *Hydro 2011*, Prague, Cz.

Brown, A., S. Müller and Z. Dobrotkova (2011), *Renewable Energy – Markets and Prospects by Technology*. Information Paper, November, OECD/IEA, Paris.

British Petroleum (BP) (2012), *Statistical Review of World Energy 2012*, www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481 retrived 1 August 2012.

Buchan, D. (2012), *The Energiewende – Germany's Gamble*, SP26, Oxford Institute for Energy Studies, University of Oxford, UK, June.

CDM Watch (2012), *Hydropower Projects in the CDM*, Policy Brief, www.internationalrivers.org/files/attached-files/120228_hydro-power-brief_lr_web.pdf retrieved 1 August 2012.

CEA (Central electricity Authority) (2001), *Preliminary Ranking Study of Hydro Electric Schemes I to III & V to VII Volumes),* CEA, Government of India, New Delhi, October.

CEPEL, Electric Energy Research Center (2008), "Sistema de Inventário Hidroelétrico de Bacias Hidrográficas – SINV 6.0 - Manual de Metodologia" In *Technical Report DP/DEA – 1296/08*.

Costa, F.S., I.P. Raupp, J.M. Damázio, S.H.M. Pires, D.F. Matos, L.R. Paz, K. Garcia, A.M. Medeiros, P.C.P. Menezes (2011), "Hydropower Inventory Studies of River Basins in Brazil", *The International Journal on Hydropower & Dams*, vol. 18.

Dambrine, F. (2006), *Perspectives de Développement de la Production Hydroélectrique en France,* Ministère de l'économie, des finances et de l»industrie, Paris, March.

Deutsche Bank Climate Change Advisors (DBCCA) (2011), *Hydropower in China: Opportunities and risks,* October, London.

EPRI (Electric Power Research Institute) (2006), *Rehabilitating and Upgrading Hydro Power Plants - a Hydro Power Technology Round-Up Report, Volume 2 (2)*, EPRI, Palo Alto, CA.

EPRI (2010), *Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits*, EPRI, Palo Alto, CA.

Energinet (2012) *Submarine cable to Norway - Skagerrak 4*, www.energinet.dk/EN/ANLAEG-OG-PROJEKTER/Anlaegsprojekter-el/Sider/Soekabel-til-Norge-Skagerrak-4.aspx retrieved 1 August 2012.

EURELECTRIC (2011), *Hydro in Europe: Powering Renewables.* Union of the Electricity Industry – EURELECTRIC, Brussels.

Fisher, R.K. *et al.* (2012), A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe, *Hydrovision International*, Louisville, Ky, July.

Gao, H. (2012), Personal communication. Centre for Renewable Energy Development, Energy Research Institute, Beijing.

Granit, J.J., R.M. King and R. Noel (2011), "Strategic Environmental Assessment as a Tool to Develop Power in Transboundary Water Basin Settings", *International Journal on Social Ecology and Sustainable Development*, Vol.2 N°1.

Granit, J.J. and A. Lindström (2011), *"Constraints and Opportunities in Meeting the Increasing Use of Water for Energy Production",* in *A.Y. Hoekstra, M.M. Alday and B. Avril (Eds), Proceedings of the EST Strategic Workshop on Accounting for Water Scarcity and Pollution in the Rules of International Trade*, Unesco-IHE (Institute for Water Education), Delft, The Netherlands.

Hamududu, B. and A. Killingtvelt (2012), "Assessing Climate Change Impacts on Global Hydropower", *Energies*, N°5, 305-322, February.

ICOLD (International Commission on Large Dams) (2011a), *Cost savings in dams,* Bulletin Rough 144, www.icold-cigb.org

ICOLD (2011b), *World Register of Dams*, www.icold-cigb.org/GB/World_register/world_register.asp.

IEA (2011a), *World Energy Outlook.* OECD/IEA, Paris.

IEA (2011b), *Solar Energy Perspectives*, OECD/IEA, Paris.

IEA (2011c), *Harnessing Variable Renewables*: *A Guide to the Balancing Challenge* OECD/IEA, Paris.

IEA (2012a), *Electricity Information 2012.* OECD/IEA, Paris.

IEA (2012b), *Medium-Term Renewable Energy Market Report,* OECD/IEA.

IEA (2012c), *Energy Technology Perspectives 2012,* OECD/IEA.

IEA Hydro (2000a),, *Hydropower and the Environment: Effectiveness of Mitigation Measures.*

IEA Hydro (2000b), *Hydropower and the Environment: Survey of the Environmental and Social Impacts and the Effectiveness of Mitigation Measures in Hydropower Development.*

IEA Hydro (2000c), *Hydropower and the Environment: Present Context and Guidelines for Future Action. Volume I: Summary and Recommendations.*

IEA Hydro (2000d), *Hydropower and the Environment: Present Context and Guidelines for Future Action. Volume II: Main Report.*

IEA Hydro (2000e), *Hydropower and the Environment: Present Context and Guidelines for Future Action. Volume III: Appendixes.*

IEA and NEA (Nuclear Energy Agency) (2010), *Projected Costs of Generating Electricity* – 2010 Edition, OECD/NEA/IEA, Paris.

IEA Wind (2011), *Integration of Wind and Hydropower Systems*, Task 24 Final Technical Report, www.ieawind.org/index_page_postings/task24/task%2024%20Vol%201%20Final.pdf retrieved 1 August 2012.

IHA (International Hydropower Association) (2010), *Hydropower Sustainability Assessment Protocol*¸ November, www.hydrosustainability.org/IHAHydro4Life/media/PDFs/Protocol/hydropower-sustainability-assessment-protocol_web.pdf retrieved 1 August 2012.

IJHD (International Journal on Hydropower & Dams) (2010): *World Atlas & Industry Guide.* Wallington, Surrey, UK.

Inage, S. (2009), *Prospects for Large-Scale Energy Storage in Decarbonised Power Grids,* IEA Working Paper, IEA/OECD, Paris.

Ingram, E. (2009), “Pumped Hydro Development Activity Snapshots”, *Hydro Review* 17(6).

IRENA (International Renewable Energy Agency) (2012), *Renewable Energy Technologies: Cost Analysis Series, Volume 1: Power Sector, Issue 3/5, Hydropower.* Working Paper, IRENA, June.

IPCC (Intergovernmental Panel on Climate Change) (2007), *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the IPCC: Technical Summary. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC (2011), *Renewable Energy Sources and Climate Change Mitigation*, Special Report prepared by Working Group III of the IPCC: Executive Summary. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kaikkonen, R., N.M.Nielsen & L.Nielsen (2010). *IEA Hydropower’s Update of Annex III: Hydropower and the Environment* Hydropower ‘10, Tromsø, Norway. 1st to 3rd February.

Kema (2007), *Energy Island for large-scale Electricity Storage,* www.kema.com/services/ges/innovative-projects/energystorage/Default.aspx retrieved 1 August 2012.

Lacal Arantegui, R., N. Fitzgerald and P. Leahy (2012), *Pumped-hydro Energy Storage: Potential for Transformation from Single Dams*, European Commission Joint Research Centre, Institute for Energy and Transport, Petten, NL.

Lempérière, F. (2008), “The Emerald Lakes: Large Offshore Storage Basins for Renewable Energy”, *Hydropower and Dams,* Issue One.

Lempérière, F. (2010), *Most world energy will be guaranteed by P.S.P.*, Hydrocoop, September.

Lempérière, F. (2011), *Stockage d’Energie par STEP Marines*, Hydrocoop, Paris.

Lier, O.E. (2011), *Rehabilitation of Hydropower – an untapped resource?* presentation at a Workshop on Rehabilitation of Hydropower, The World Bank, 12-13 October, Washington D.C.

MEA (Millennium Ecosystem Assessment) (2005), *Ecosystems and human well-being: Wetlands and water synthesis*. World Resources Institute, Washington, DC.

Maceira, M.E.P. *et al.* (2002). *Chain of Optimization Models for Setting the Energy Dispatch and Spot Price in the Brazilian System*, XIV Power Systems Computation Conference, Seville, Spain.

Maceira, M.E.P. *et al.* (2008). *Ten Years of Application of Stochastic Dual Dynamic Programming in Official and Agents Studies in Brazil – Description of the NEWAVE Program,* XVI Power Systems Computation Conference, Glasgow, Scotland.

March, P. (2011), "Hydraulic and Environmental Performance of Aerating Turbine Technologies," *Proceedings of EPRI/DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers*, Palo Alto, California: EPRI, Report No. 1024609, December.

Melo, A.C.G., M.P. Zimmermann, M.E.P. Maceira, and F.R. Wojcicki (2012), *Sustainable Development of Hydropower in Brazil – Technical and Institutional Aspects*, 49, 2012 Session of the CIGRÉ - International Council on Large Electric Systems, Paris, France, 26th to 31st August.

MME/EPE (Ministry of Mines and Energy/Energy Research Company) (2007), *Brazil´s National Energy Plan - PNE 2030*. Available for download at www.mme.gov.br.

MME/EPE (2011), *Brazil's 10-year Energy Plan 2020 - PDE 2020*", Available for download at www.mme.gov.br.

MME/CEPEL (Ministry of Mines and Energy/Electric Energy Research Center) (2007), *Manual for Hydropower Inventory Studies of River Basins - 2007 Edition*. Available for download at www.cepel.br.

Mirumachi, N. and J. Torriti (forthcoming), "The Use of Public Participation and Economic Appraisal for Public Involvement in Large-Scale Hydropower Projects: Case Study of the Nam Theun 2 Hydropower Project", *Energy Policy,* forthcoming.

Nielsen, N.M. and N.K.Blaikie (2010) *Best Practice Management of Hydroplant Overhaul and Retrofits.* ASIA 2010. Kuching, Sarawak, Malaysia 29th and 30th March.

NREL (National Renewable Energy Laboratory) (2009), "Scenario Development and Analysis of Hydrogen as a Large-Scale Energy Storage Medium", presentation at the *RMEL meeting*, Denver, US, 10 June.

Pittock, J. (2010), "Viewpoint - Better Management of Hydropower in an Era of Climate Change", *Water Alternatives* 3(2): 444-452.

REN21 (Renewable Energy Policy Network for the 21st Century) (2011), *Renewables 2011 Global Status Report.* Unep, Paris.

Steffen, B. (2012), Prospects for pumped-hydro storage in Germany, *Energy Policy* n°45: 420-429

Stepan, M. (2011), *The 3-Phase Approach*, presentation at a Workshop on Rehabilitation of Hydropower, The World Bank, 12-13 October, Washington D.C.

Verarga, W. and S.M. Scholz (eds.) (2011), *Assessment of the Risk of Amazon Dieback*, The World Bank Group, Washington D.C.

WCD (World Commission on Dams) (2000), *Dams and Development – A New Framework for Decision-Making*, Earthscan, London, November.

World Bank (2003), *Water Resources Sector Strategy,* The World Bank Group, Washington D.C.

World Bank (2009), *Directions in Hydropower,* The World Bank Group, Washington D.C.

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Technology Roadmap Hydropower

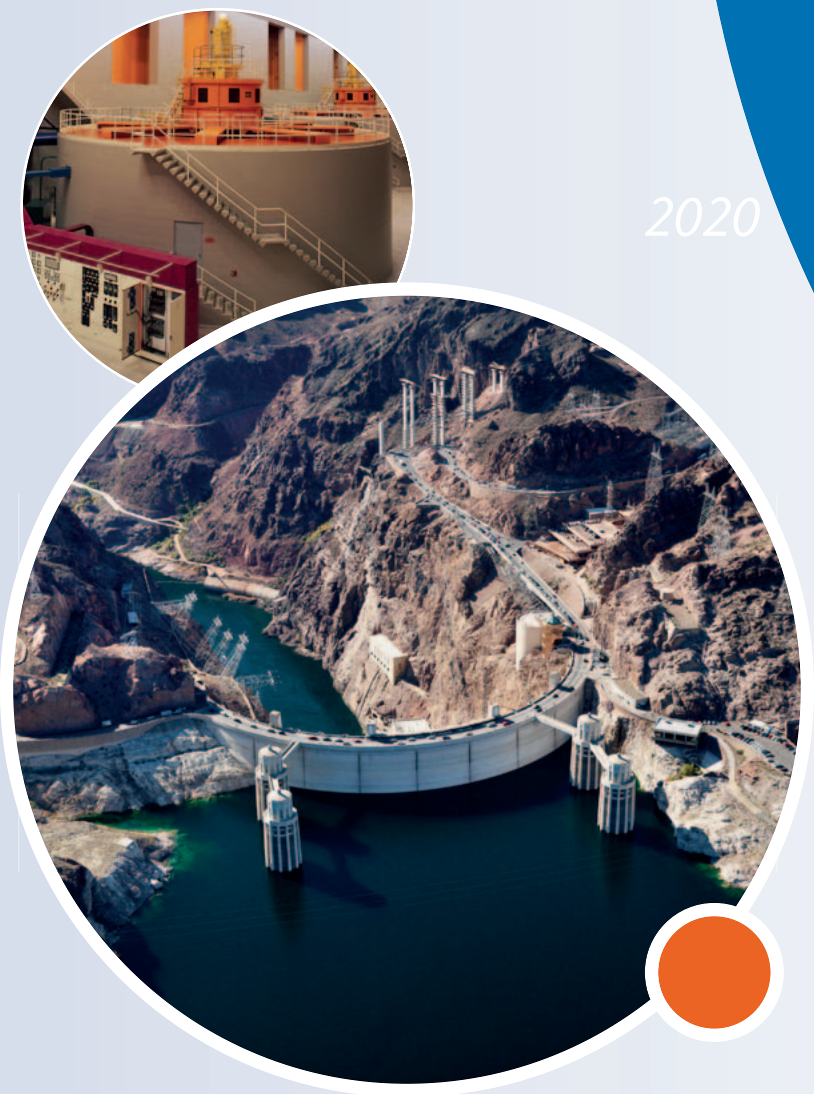
2010

2015

2020

2025

2030



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