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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation dedicated to renewable energy.
In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.
As of May 2012, the membership of IRENA comprised 158 States and the European Union (EU), out of which 94 States and the EU have ratified the Statute.

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Preface

Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy.

Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today. Tens of gigawatts of wind, hydropower and solar photovoltaic capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies' costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

International Renewable Energy Agency (IRENA) Member Countries have asked for better, objective cost data for renewable energy technologies. This working paper aims to serve that need and is part of a set of five reports on hydropower, wind, biomass, concentrating solar power and solar pholtovoltaics that address the current costs of these key renewable power technology options. The reports provide valuable insights into the current state of deployment, types of technologies available and their costs and performance. The analysis is based on a range of data sources with the objective of developing a uniform dataset that supports comparison across technologies of different cost indicators - equipment, project and levelised cost of electricity – and allows for technology and cost trends, as well as their variability to be assessed.

The papers are not a detailed financial analysis of project economics. However, they do provide simple, clear metrics based on up-to-date and reliable information which can be used to evaluate the costs and performance of different renewable power generation technologies. These reports help to inform the current debate about renewable power generation and assist governments and key decision makers to make informed decisions on policy and investment.

The dataset used in these papers will be augmented over time with new project cost data collected from IRENA Member Countries. The combined data will be the basis for forthcoming IRENA publications and toolkits to assist countries with renewable energy policy development and planning. Therefore, we welcome your feedback on the data and analysis presented in these papers, and we hope that they help you in your policy, planning and investment decisions.

Dolf Gielen

Director, Innovation and Technology

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Key findings

1. **Average investment costs** for large hydropower plants with storage typically range from as low as USD 1 050/kW to as high as USD 7 650/kW while the range for small hydropower projects is between USD 1 300/kW and USD 8 000/kW. Adding additional capacity at existing hydropower schemes or existing dams that don't have a hydropower plant can be significantly cheaper, and can cost as little as USD 500/kW.

Table 1: Typical installed costs and LCOE of hydropower projects

	Installed costs (USD/kW)	Operations and maintenance costs (%/year of installed costs)	Capacity factor (%)	Levelised cost of electricity (2010 USD/kWh)
Large hydro	1 050 – 7 650	2 – 2.5	25 to 90	0.02 – 0.19
Small hydro	1 300 – 8 000	1 – 4	20 to 95	0.02 – 0.27
Refurbishment/upgrade	500 – 1 000	1 – 6		0.01 – 0.05

Note: The levelised cost of electricity calculations assume a 10% cost of capital

2. **Annual operations and maintenance costs** (O&M) are often quoted as a percentage of the investment cost per kW. Typical values range from 1% to 4%. Large hydropower projects will typically average around 2% to 2.5%. Small hydropower projects don't have the same economies of scale and can have O&M costs of between 1% and 6%, or in some cases even higher.

3. **The cost of electricity generated** by hydropower is generally low although the costs are very site-specific. The levelised cost of electricity (LCOE) for hydropower refurbishments and upgrades ranges from as low as USD 0.01/kWh for additional capacity at an existing hydropower project to around USD 0.05/kWh for a more expensive upgrade project assuming a 10% cost of capital. The LCOE for large hydropower projects typically ranges from USD 0.02 to USD 0.19/kWh assuming a 10% cost of capital, making the best hydropower power projects the most cost competitive generating option available today. The LCOE range for small hydropower projects for a number of real world projects in developing countries evaluated by IRENA was between USD 0.02 and USD 0.10/kWh, making small hydro a very cost competitive option to supply electricity to the grid, or to supply off-grid rural electrification schemes. Very small hydropower projects can have higher costs than this and can have an LCOE of USD 0.27/kWh or more for pico-hydro systems.

4. **Significant hydropower** potential remains unexploited. The technical potential is some 4.8 times greater than today's electricity generation. The total worldwide technical potential for hydropower is estimated at 15 955 TWh/year.

5. **Hydropower, when associated with storage** in reservoirs, contributes to the stability of the electrical system by providing flexibility and grid services. Hydropower can help with grid stability, as spinning turbines can be ramped up more rapidly than any other generation source. Additionally, with large reservoirs, hydropower can store energy over weeks, months, seasons or even years. Hydropower can therefore provide the full range of ancillary services required for the high penetration of variable renewable energy sources, such as wind and solar.

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1. Introduction

Renewable energy technologies can help countries meet their policy goals for secure, reliable and affordable energy to expand electricity access and promote development. This paper is part of a series on the cost and performance of renewable energy technologies produced by IRENA. The goal of these papers is to assist government decision-making and ensure that governments have access to up-to-date and reliable information on the costs and performance of renewable energy technologies.

Without access to reliable information on the relative costs and benefits of renewable energy technologies it is difficult, if not impossible, for governments to arrive at an accurate assessment of which renewable energy technologies are the most appropriate for their particular circumstances. These papers fill a significant gap in publically available information because there is a lack of accurate, comparable, reliable and up-to-date data on the costs and performance of renewable energy technologies. The rapid growth in installed capacity of renewable energy technologies and the associated cost reductions mean that even data one or two years old can significantly overestimate the cost of electricity from renewable energy technologies although this is not generally the case for hydropower, which is a mature technology. There is also a significant amount of perceived knowledge about the cost and performance of renewable power generation that is not accurate, or indeed even misleading. Conventions on how to calculate cost can influence the outcome significantly, and it is imperative that these are well-documented.

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies is therefore a significant barrier to the uptake of these technologies. Providing this information will help governments, policy-makers, investors and utilities make informed decisions about the role renewables can play in their power generation mix. This paper examines the fixed and variable cost components of hydropower by country and region and provides the levelised cost of electricity from hydropower, given a number of key assumptions. This up-to-date analysis of the costs of generating electricity from hydropower will allow a fair comparison of hydropower with other generating technologies.[1]

1.1 DIFFERENT MEASURES OF COST

Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. wind and hydropower turbines, PV modules, solar reflectors), replacement costs, financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs and the levelised cost of energy (LCOE).

The analysis of costs can be very detailed, but for purposes of comparison and transparency, the approach used here is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improved transparency and confidence in the analysis, as well as facilitating the *comparison* of costs by country or region for the same technologies in order to identify what are the key drivers in any differences.

The three indicators that have been selected are:

- Equipment cost (factory gate "free on board" and delivered at site "cost, insurance and freight");
- Total installed project cost, including fixed financing costs[2]; and
- The levelised cost of electricity LCOE.

1 *IRENA, through its other work programmes, is also looking at the costs and benefits, as well as the macro-econimic impacts, of renewable power generation technologies. See WWW.IRENA.ORG for further details.*

2 *Banks or other financial institutions will often charge a fee, usually a percentage of the total funds sought, to arrange the debt financing of a project. These costs are often reported separately under project development costs.*

The analysis in this paper focuses on estimating the cost of hydropower energy from the perspective of an individual investor, whether it is a state-owned electricity generation utility, an independent power producer, an individual or a community looking to invest in renewables (Figure 1.1). The analysis excludes the impact of government incentives or subsidies, system balancing costs associated with variable renewables and any system-wide cost-savings from the merit order effect[3]. Further, the analysis does not take into account any CO_2 pricing, nor the benefits of renewables in reducing other externalities (e.g. reduced local air pollution, contamination of natural environments). Similarly, the benefits of renewables being insulated from volatile fossil fuel prices have not been quantified. These issues are important but are covered by other programmes of work at IRENA.

It is important to include clear definitions of the technology categories, where this is relevant, to ensure that cost comparisons are robust and provide useful insights (e.g. small hydro vs. large hydro, run-of-river vs. pumped hydro). It is also useful to identify any additional functionality and/or qualities of the renewable power generation technologies being investigated (e.g. the ability to store water for later generation and provide ancillary grid services). It is vital to ensure that system boundaries for costs are clearly set and that the available data are directly comparable.

The data used for the comparisons in this paper come from a variety of sources, such as business journals, industry associations, consultancies, governments, auctions and tenders. Every effort has been made to ensure that these data are directly comparable and are for the same system boundaries. Where this is not the case, the data have been corrected to a common basis using the best available data or assumptions. It is planned that these data will be complemented by detailed surveys of real world project data in forthcoming work by the Agency.

An important point is that, although this paper tries to examine costs, strictly speaking, the data available are actually prices, and not even true market average prices, but price indicators. The difference between costs and prices is determined by the amount above, or below, the normal profit that would be seen in a competitive market.

The cost of equipment at the factory gate is often available from market surveys or from other sources. A key difficulty is often reconciling different sources of data to identify why data for the same period differs. The balance of capital costs in total project costs

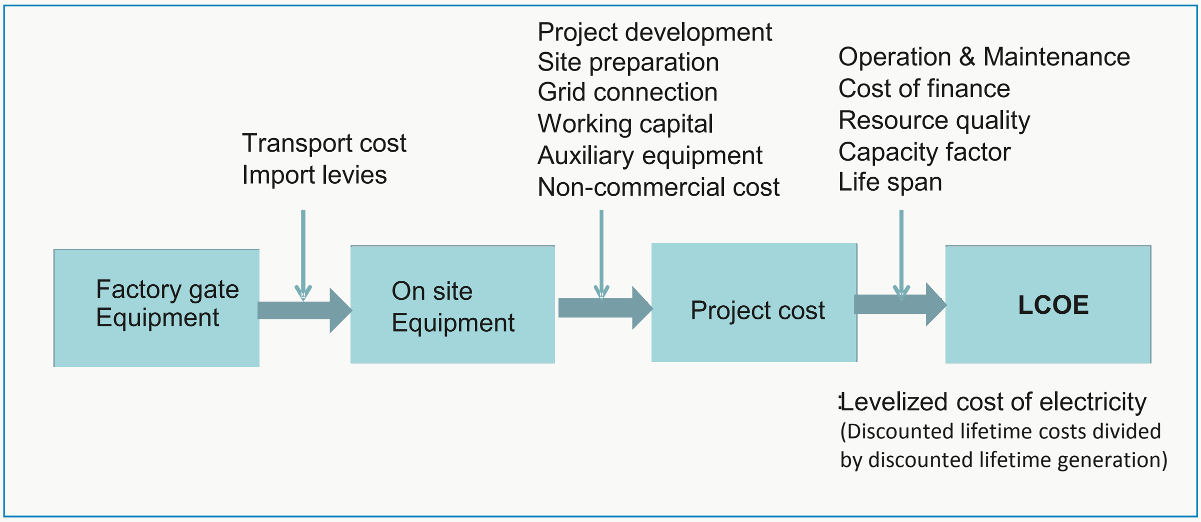

Figure 1.1: Renewable power generation cost indicators and boundaries

3 See EWEA, ***Wind Energy and Electricity Prices,*** *April 2010 for a discussion*

tends to vary even more widely than power generation equipment costs as it is often based on significant local content, which depends on the cost structure of where the project is being developed. Total installed costs can therefore vary significantly by project, country and region depending on a wide range of factors.

1.2 LEVELISED COST OF ELECTRICITY GENERATION

The LCOE of renewable energy technologies varies by technology, country and project based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The approach used in the analysis presented here is based on a discounted cash flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) over the project lifetime to a common basis, taking into consideration the time value of money. Given the capital-intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), often also referred to as the discount rate[4], used to evaluate the project has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. However, this has the additional advantage that the analysis is transparent and easy to understand. In addition, a more detailed LCOE analysis results in a significantly higher overhead in terms of the granularity of assumptions required. This often gives the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based on real world data, then the "accuracy" of the approach can be misleading.

The formula used for calculating the LCOE of renewable energy technologies is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

LCOE = the average lifetime levelised cost of electricity generation;
I_t = investment expenditures in the year **t**;
M_t = operations and maintenance expenditures in the year **t**;
F_t = fuel expenditures in the year **t**;
E_t = electricity generation in the year **t**;
r = discount rate; and
n = economic life of the system.

All costs presented in this paper are real 2010 USD, that is to say after inflation has been taken into account.[5] The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

As already mentioned, although different cost measures are useful in different situations, the LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development. Similarly, more detailed discounted cash flow approaches that take into account taxation, subsidies and other incentives will be used by renewable energy project developers to assess the profitability of real world projects.

4 These are not necessarily the same but in the analysis in this paper are assumed to be equivalent values.
5 An analysis based on nominal values with specific inflation assumptions for each of the cost components is beyond the scope of this analysis. Project developers will develop their own specific cash flow models to identify the profitability of a project from their perspective.

2. HYDROPOWER TECHNOLOGIES AND RESOURCES

2.1 INTRODUCTION

Hydropower is a renewable energy source based on the natural water cycle. Hydropower is the most mature, reliable and cost-effective renewable power generation technology available (Brown, 2011). Hydropower schemes often have significant flexibility in their design and can be designed to meet base-load demands with relatively high capacity factors, or have higher installed capacities and a lower capacity factor, but meet a much larger share of peak demand.

Hydropower is the largest renewable energy source, and it produces around 16 % of the world's electricity and over four-fifths of the world's renewable electricity. Currently, more than 25 countries in the world depend on hydropower for 90 % of their electricity supply (99.3 % in Norway), and 12 countries are 100 % reliant on hydro. Hydro produces the bulk of electricity in 65 countries and plays some role in more than 150 countries. Canada, China and the United States are the countries which have the largest hydropower generation capacity (IPCC, 2011; REN21, 2011; and IHA, 2011).

Hydropower is the most flexible source of power generation available and is capable of responding to demand fluctuations in minutes, delivering base-load power and, when a reservoir is present, storing electricity over weeks, months, seasons or even years (Brown, 2011 and IPCC, 2011). One key advantage of hydropower is its unrivalled "load following" capability (i.e. it can meet load fluctuations minute-by-minute). Although other plants, notably conventional thermal power plants, can respond to load fluctuations, their response times are not as fast and often are not as flexible over their full output band. In addition to grid flexibility and security services (spinning reserve), hydropower dams with large reservoir storage be used to store energy over time to meet system peaks or demand decoupled from inflows. Storage can be over days, weeks, months, seasons or even years depending on the size of the reservoir.

As a result of this flexibility, hydropower is an ideal complement to variable renewables as, when the sun shines or the wind blows, reservoir levels can be allowed to increase for a time when there is no wind or sunshine. Similarly, when large ramping up or down of supply is needed due to increases or decreases in solar or wind generation, hydro can meet these demands. Hydroelectric generating units are able to start up quickly and operate efficiently almost instantly, even when used only for one or two hours. This is in contrast to thermal plant where start-up can take several hours or more, during which time efficiency is significantly below design levels. In addition, hydropower plants can operate efficiently at partial loads, which is not the case for many thermal plants.[6] Reservoir and pumped storage hydropower can be used to reduce the frequency of start-ups and shutdowns of conventional thermal plants and maintain a balance between supply and demand, thereby reducing the load-following burden of thermal plants (Brown, 2011).

Hydropower is the only large-scale and cost-efficient storage technology available today. Despite promising developments in other energy storage technologies, hydropower is still the only technology offering economically viable large-scale storage. It is also a relatively efficient energy storage option.

6 *Although many modern gas-fired plants can operate within one or two percentage points of their design efficiency over a relatively wide load range, this is usually not the case for older plants and coal-fired plants. Start-stop operation at partial loads for short periods therefore implies low efficiencies, will often increase O&M costs and may prematurely shorten the life of some components.*

The system integration capabilities of hydropower are therefore particularly useful for allowing the large-scale large penetration of wind and other variable power sources (IEA, 2010c). Systems with significant shares of large-scale hydro with significant reservoir storage will therefore be able to integrate higher levels of variable renewables at low cost than systems without the benefit of hydropower.

Hydropower can serve as a power source for both large, centralized and small, isolated grids. Small hydropower can be a cost-competitive option for rural electrification for remote communities in developed and developing countries and can displace a significant proportion of diesel-fired generation. In developing countries, another advantage of hydropower technology is that it can have important multiplier effects by providing both energy and water supply services (e.g. flood control and irrigation), thus bringing social and economic benefits.

Hydropower is generally CO_2-free in operation,[7] but there are GHG emissions from the construction of hydropower schemes[8], from silting in the reservoirs and from the decomposition of organic material (predominantly an issue in tropical regions). Hydropower schemes can have an important spatial and visual footprint. One of the greatest challenges with the development of hydropower is ensuring that the design and construction of hydropower projects is truly sustainable. This means that, in addition to an economic assessment, proper social and environmental impact assessments must be conducted and if there are negative impacts on local populations, ecosystems and biodiversity, these issues need to be mitigated in the project plan. In the past, this is an area where hydropower has had a poor track record in some cases.

Some of the more important impacts that need to be considered and mitigated include changes in river flow regimes, water quality, changes in biodiversity, population displacement and the possible effects of dams on fish migration.[9]

Although hydropower technologies are mature, technological innovation and R&D into variable-speed generation technology, efficient tunnelling techniques, integrated river basin management, hydrokinetics, silt erosion resistant materials and environmental issues (e.g. fish-friendly turbines) will provide continuous improvement of environmental performance and, in many cases, costs reductions (IPCC, 2011).

2.2 HYDROPOWER TECHNOLOGIES

Hydropower has been used by mankind since ancient times. The energy of falling water was used by the Greeks to turn waterwheels that transferred their mechanical energy to a grinding stone to turn wheat into flour more than 2000 years ago. In the 1700s, mechanical hydropower was used extensively for milling and pumping.

The modern era of hydropower development began in 1870 when the first hydroelectric power plant was installed in Cragside, England. The commercial use of hydropower started in 1880 in Grand Rapids, Michigan, where a dynamo driven by a water turbine was used to provide theatre and store front lighting (IPCC, 2011). These early hydropower plants had small capacities by today's standards but pioneered the development of the modern hydropower industry.

Hydropower schemes range in size from just a few watts for pico-hydro to several GW or more for large-scale projects. Larger projects will usually contain a number of turbines, but smaller projects may rely on just one turbine. The two largest hydropower projects in the world are the 14 GW Itaipu project in Brazil and the Three Gorges project in China with 22.4 GW. These two projects alone produce 80 to 100 TWh/year (IPCC, 2011).

Large hydropower systems tend to be connected to centralised grids in order to ensure that there is enough demand to meet their generation capacity. Small hydropower plants can be, and often are, used in isolated areas off-grid or in mini-grids. In isolated grid systems, if large reservoirs are not possible, natural seasonal flow variations might require that hydropower plants be combined with other generation sources in order to ensure continuous supply during dry periods.

7 Hydropower projects account for an estimated half of all "certified emissions reduction" credits in the CDM pipeline for renewable energy projects (Branche, 2012).

8 These can be direct (e.g. CO_2 emissions from construction vehicles) or indirect (e.g. the CO_2 emissions from the production of cement).

9 The International Hydropower Association has a "hydropower sustainability assessment protocol" that enables the production of a sustainability profile for a project through the assessment of performance within important sustainability. www.hydropower.org.

Hydropower transforms the potential energy of a mass of water flowing in a river or stream with a certain vertical fall (termed the "head"[10]). The potential annual power generation of a hydropower project is proportional to the head and flow of water. Hydropower plants use a relatively simple concept to convert the energy potential of the flowing water to turn a turbine, which, in turn, provides the mechanical energy required to drive a generator and produce electricity (Figure 2.1).

The main components of a conventional hydropower plant are:

- *Dam*: Most hydropower plants rely on a dam that holds back water, creating a large water reservoir that can be used as storage. There may also be a de-silter to cope with sediment build-up behind the dam.

- *Intake, penstock and surge chamber:* Gates on the dam open and gravity conducts the water through the penstock (a cavity or pipeline) to the turbine. There is sometimes a head race before the penstock. A surge chamber or tank is used to reduce surges in water pressure that could potentially damage or lead to increased stresses on the turbine.

- *Turbine:* The water strikes the turbine blades and turns the turbine, which is attached to a generator by a shaft. There is a range of configurations possible with the generator above or next to the turbine. The most common type of turbine for hydropower plants in use today is the Francis Turbine, which allows a side-by-side configuration with the generator.

- *Generators:* As the turbine blades turn, the rotor inside the generator also turns and electric current is produced as magnets rotate inside the fixed-coil generator to produce alternating current (AC).

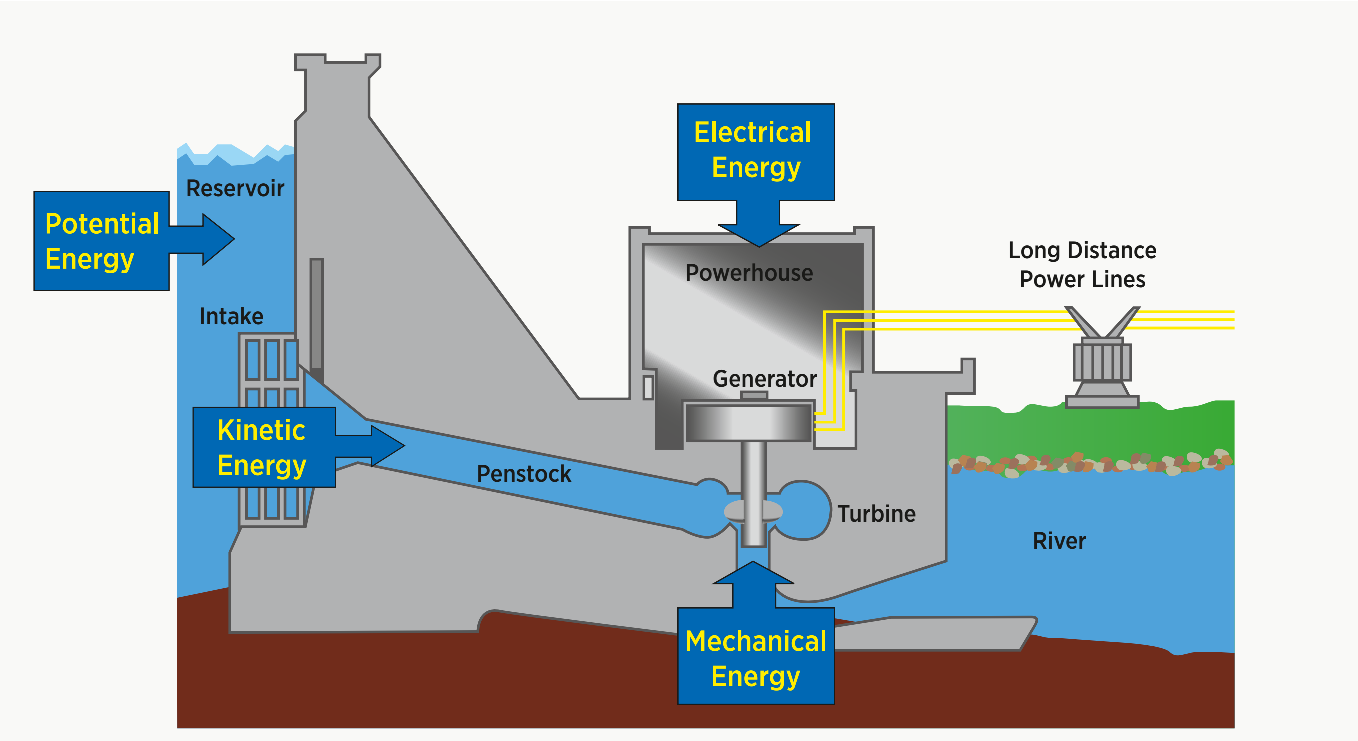

Figure 2.1: Typical "low head" hydropower plant with storage
(Picture adapted from Hydropower News and Information (http://www.alternative-energy-news.info/technology/hydro/)

10 *"Head" refers to the vertical height of the fall of a stream or river. Higher heads provide a greater pressure and therefore greater hydropower potential.*

» *Transformer*: The transformer inside the powerhouse takes the AC voltage and converts it into higher-voltage current for more efficient (lower losses) long-distance transport.

» *Transmission lines:* Send the electricity generated to a grid-connection point, or to a large industrial consumer directly, where the electricity is converted back to a lower-voltage current and fed into the distribution network. In remote areas, new transmission lines can represent a considerable planning hurdle and expense.

» *Outflow:* Finally, the used water is carried out through pipelines, called tailraces, and re-enters the river downstream. The outflow system may also include "spillways" which allow the water to bypass the generation system and be "spilled" in times of flood or very high inflows and reservoir levels.

Hydropower plants usually have very long lifetimes and, depending on the particular component, are in the range 30 to 80 years. There are many examples of hydropower plants that have been in operation for more than 100 years with regular upgrading of electrical and mechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels) (IPCC, 2011).

The water used to drive hydropower turbines is not "consumed" but is returned to the river system. This may not be immediately in front of the dam and can be several kilometres or further downstream, with a not insignificant impact on the river system in that area. However, in many cases, a hydropower system can facilitate the use of the water for other purposes or provide other services such as irrigation, flood control and/or more stable drinking water supplies. It can also improve conditions for navigation, fishing, tourism or leisure activities.

The components of a hydropower project that require the most time and construction effort are the dam, water intake, head race, surge chamber, penstock, tailrace and powerhouse. The penstock conveys water under pressure to the turbine and can be made of, or lined with, steel, iron, plastics, concrete or wood. The penstock is sometimes created by tunnelling through rock, where it may be lined or unlined.

The powerhouse contains most of the mechanical and electrical equipment and is made of conventional building materials although in some cases this maybe underground. The primary mechanical and electrical components of a small hydropower plant are the turbines and generators.

Turbines are devices that convert the energy from falling water into rotating shaft power. There are two main turbine categories: "reactionary" and "impulse". Impulse turbines extract the energy from the momentum of the flowing water, as opposed to the weight of the water. Reaction turbines extract energy from the pressure of the water head.

The most suitable and efficient turbine for a hydropower project will depend on the site and hydropower scheme design, with the key considerations being the head and flow rate (Figure 2.2). The Francis turbine is a reactionary turbine and is the most widely used hydropower turbine in existence. Francis turbines are highly efficient and can be used for a wide range of head and flow rates. The Kaplan reactionary turbine was derived from the Francis turbine but allows efficient hydropower production at heads between 10 and 70 metres, much lower than for a Francis turbine. Impulse turbines such as Pelton, Turgo and cross-flow (sometimes referred to as Banki-Michell or Ossberger) are also available. The Pelton turbine is the most commonly used turbine with high heads. Banki-Michell or Ossberger turbines have lower efficiencies but are less dependent on discharge and have lower maintenance requirements.

There are two types of generators that can be used in small hydropower plants: asynchronous (induction)

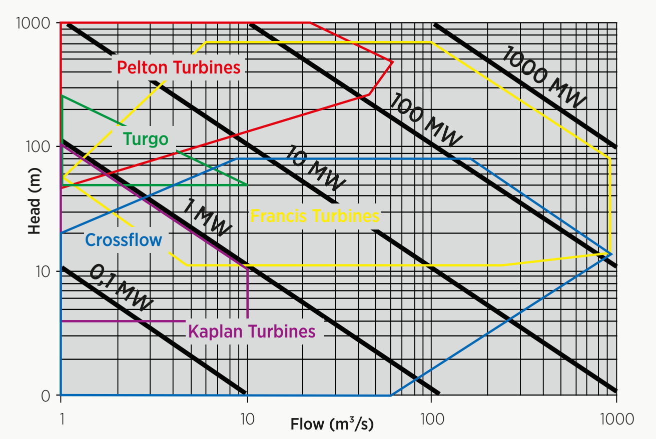

Figure 2.2: Working areas of different turbine types

Source: Based on NHA and HRF, 2010.

and synchronous machines (NHA and HRF, 2010). Asynchronous generators are generally used for micro-hydro projects.

Small hydropower, where a suitable site exists, is often a very cost-effective electric energy generation option. It will generally need to be located close to loads or existing transmission lines to make its exploitation economic. Small hydropower schemes typically take less time to construct than large-scale ones although planning and approval processes are often similar (Egre and Milewski, 2002).

Large-scale hydropower plants with storage can largely de-couple the timing of hydropower generation from variable river flows. Large storage reservoirs may be sufficient to buffer seasonal or multi-seasonal changes in river flows, whereas smaller reservoirs may be able to buffer river flows on a daily or weekly basis.

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), hydropower plants can generate power at a near-constant level throughout the year (i.e. operate as a base-load plant). Alternatively, if the scheme is designed to have hydropower capacity that far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as a peaking plant and is designed to be able to generate large quantities of electricity to meet peak electricity system demand. Where the site allows, these are design choices that will depend on the costs and likely revenue streams from different configurations.

2.3 HYDROPOWER CLASSIFICATION BY TYPE

Hydropower plants can be constructed in a variety of sizes and with different characteristics. In addition to the importance of the head and flow rate, hydropower schemes can be put into the following categories:[11]

- *Run-of-river* hydropower projects have no, or very little, storage capacity behind the dam and generation is dependent on the timing and size of river flows.
- *Reservoir* (storage) hydropower schemes have the ability to store water behind the dam in a reservoir in order to de-couple generation from hydro inflows. Reservoir capacities can be small or very large, depending on the characteristics of the site and the economics of dam construction.
- *Pumped storage* hydropower schemes use off-peak electricity to pump water from a reservoir located after the tailrace to the top of the reservoir, so that the pumped storage plant can generate at peak times and provide grid stability and flexibility services.

These three types of hydropower plants are the most common and can be developed across a broad spectrum of size and capacity from the very small to very large, depending on the hydrology and topography of the watershed. They can be grid-connected or form part of an isolated local network.

Run-of-river technologies

In run-of-river (ROR) hydropower systems (and reservoir systems), electricity production is driven by the natural flow and elevation drop of a river. Run-of-river schemes have little or no storage, although even run-of-river schemes without storage will sometimes have a dam.[12] Run-of-river hydropower plants with storage are said to have "pondage". This allows very short-term water storage (hourly or daily). Plants with pondage can regulate water flows to some extent and shift generation a few hours or more over the day to when it is most needed. A plant without pondage has no storage and therefore cannot schedule its production. The timing of generation from these schemes will depend on river flows. Where a dam is not used, a portion of the river water might be diverted to a channel or pipeline (penstock) to convey the water to the turbine.

11 In addition to these established and mature hydropower technologies, so-called "in-stream" hydropower technologies allow the generation of electricity without disruption to the river system and cost of dam construction. In-stream hydropower technologies have yet to be deployed at scale and are beyond the scope of this report. However, R&D is progressing and they have a number of interesting features that mean that it is worth pursuing.

12 The definition of "run-of-river" hydropower projects varies around the world. A strict definition is that it is a system without storage, but in many countries this is applied to systems with several hours or even days of storage.

Run-of-river schemes are often found downstream of reservoir projects as one reservoir can regulate the generation of one or many downstream run-of-river plant. The major advantage of this approach is that it can be less expensive than a series of reservoir dams because of the lower construction costs. However, in other cases, systems will be constrained to be run-of-river because a large reservoir at the site is not feasible.

The operation regime of run-of-river plants, with and without pondage, depends heavily on hydro inflows. Although it is difficult to generalise, some systems will have relatively stable inflows while others will experience wide variations in inflows. A drawback of these systems is that when inflows are high and the storage available is full, water will have to be "spilled". This represents a lost opportunity for generation and the plant design will have to trade off capacity size to take advantage of high inflows, with the average amount of time these high inflows occur in a normal year. The value of the electricity produced will determine what the trade-off between capacity and spilled water will be and this will be taken into account when the scheme is being designed.

Hydropower schemes with reservoirs for storage

Hydropower schemes with large reservoirs behind dams can store significant quantities of water and effectively act as an electricity storage system. As with other hydropower systems, the amount of electricity that is generated is determined by the volume of water flow and the amount of hydraulic head available.

The advantage of hydropower plants with storage is that generation can be decoupled from the timing of rainfall or glacial melt. For instance, in areas where snow melt provides the bulk of inflows, these can be stored through spring and summer to meet the higher electricity demand of winter in cold climate countries, or until summer to meet peak electricity demands for cooling. Hydropower schemes with large-scale reservoirs thus offer unparalleled flexibility to an electricity system.

The design of the hydropower plant and the type and size of reservoir that can be built are very much dependent on opportunities offered by the topography and are defined by the landscape of the plant site. However, improvements in civil engineering techniques that reduce costs mean that what is economic is not fixed. Reduced costs for tunnelling or canals can open up increased opportunities to generate electricity.

Hydropower can facilitate the low-cost integration of variable renewables into the grid, as it is able to respond almost instantaneously to changes in the amount of electricity running through the grid and to effectively store electricity generated by wind and solar by holding inflows in the reservoir rather than generating. This water can then be released when the sun is not shining or the wind not blowing. In Denmark, for example, the high level of variable wind generation (>20 % of the annual electricity production) is managed in part through interconnections to Norway where there is substantial hydropower storage (Nordel, 2008a).

Pumped storage hydropower technologies

Pumped hydro plants allow off-peak electricity to be used to pump water from a river or lower reservoir up to a higher reservoir to allow its release during peak times. Pumped storage plants are not energy sources but instead are storage devices. Although the losses of the pumping process contribute to the cost of storage, they are able to provide large-scale energy storage and can be a useful tool for providing grid stability services and integrating variable renewables, such as wind and solar.

Pumped storage and conventional hydropower with reservoir storage are the only large-scale, low-cost electricity storage options available today (Figure 2.3). Pumped storage represents about 2.2 % of all generation capacity in the United States, 18 % in Japan and 19 % in Austria (IEA, 2012 and Louis, 2012).

Pumped storage power plants are much less expensive than lead-acid and Li-ion batteries. However, an emerging solution for short-term storage are Sodium-Sulphur (NaS) batteries, but these are not as mature as pumped hydro and costs need to be confirmed (Figure 2.3). However, pumped storage plants are generally more expensive than conventional large hydropower schemes with storage, and it is often very difficult to find good sites to develop pumped hydro storage schemes.

Pumped hydropower systems can use electricity, not just at off-peak periods, but at other times where having some additional generation actually helps to reduce grid costs or improve system security. One example is where spinning reserve committed from thermal power plants

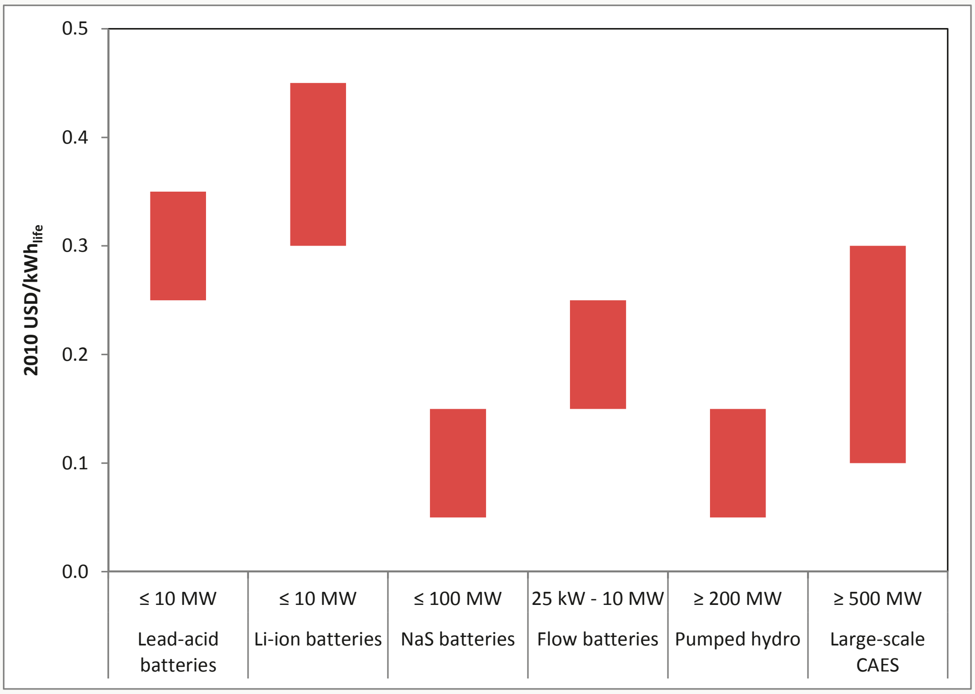

Figure 2.3: Comparison of the lifecycle cost of electricity storage systems

Source: IRENA, 2012.

would be at a level where they would operate at low, inefficient loads. Pumped hydro demand can allow them to generate in a more optimal load range, thus reducing the costs of providing spinning reserve. The benefits from pumped storage hydropower in the power system will depend on the overall mix of existing generating plants and the transmission network. However, its value will tend to increase as the penetration of variable renewables for electricity generation grows.

The potential for pumped storage is significant but not always located near demand centres. From a technical viewpoint, Norway alone has a long-term potential of 10 GW to 25 GW (35 TWh or more) and could almost double the present installed capacity of 29 GW (EURELECTRIC, 2011).

Hydropower capacity factors

The capacity factor achieved by hydropower projects needs to be looked at somewhat differently than for other renewable projects. For a given set of inflows into a catchment area, a hydropower scheme has considerable flexibility in the design process. One option is to have a high installed capacity and low capacity factor to provide electricity predominantly to meet peak demands and provide ancillary grid services. Alternatively, the installed capacity chosen can be lower and capacity factors higher, with potentially less flexibility in generation to meet peak demands and provide ancillary services.[13]

Analysis of data from CDM projects helps to emphasise this point. Data for 142 projects around the world yield capacity factors of between 23 % and 95 %. The average capacity factor was 50 % for these projects (Figure 2.4).

2.4 LARGE AND SMALL HYDROPOWER SCHEMES

A classification of hydropower by head is interesting because it is this that determines the water pressure on the turbines, which, together with discharge, are

13 This is a generalisation, and it is impossible to be categorical about this distinction as there is a continuum of possibilities over a year for each type of plant to provide all these services.

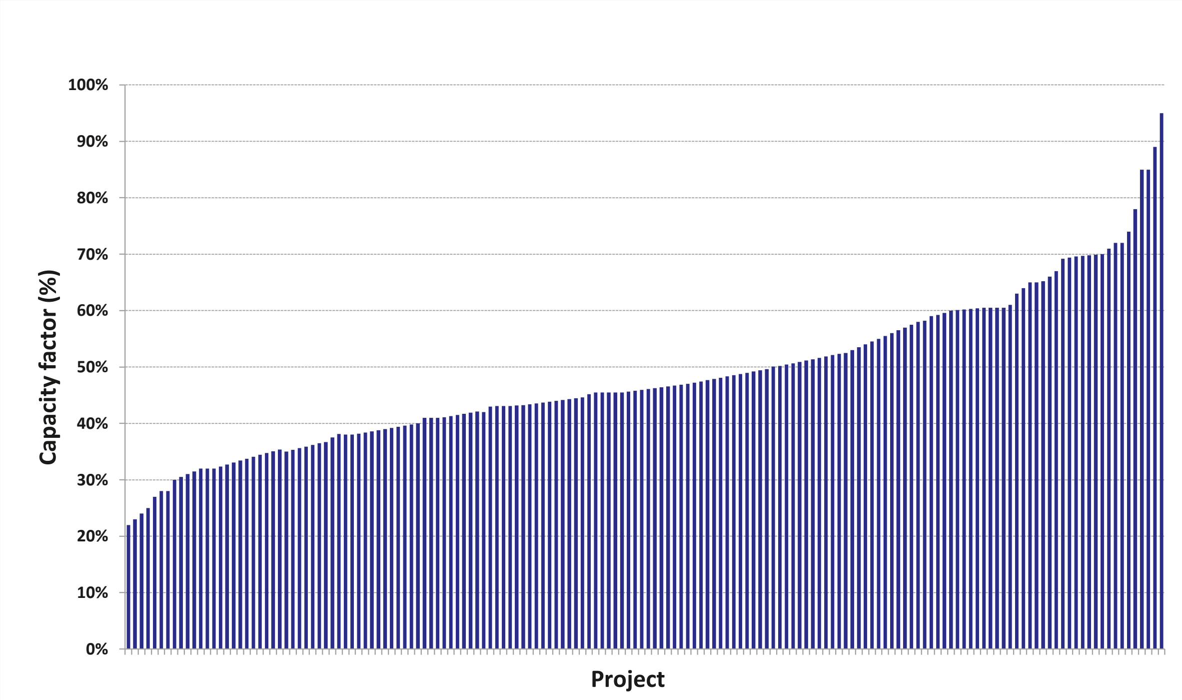

Figure 2.4: Capacity factors for hydropower projects in the Clean Development Mechanism

Source: Branche, 2011.

the most important parameters for deciding the type of hydraulic turbine to be used. However, generally speaking, hydro is usually classified by size (generating capacity) and the type of scheme (run-of-river, reservoir, pumped storage). Although there is no agreed definition, the following bands are typical to describe the size of hydropower projects:

» *Large-hydro*: 100 MW or more of capacity feeding into a large electricity grid;

» *Medium-hydro*: From 20 MW to 100 MW almost always feeding a grid;

» *Small-hydro*: From 1 MW to 20 MW usually feeding into a grid;

» *Mini-hydro*: From 100 kW to 1 MW that can be either stand-alone, mini-grid or grid-connected;

» *Micro-hydro*: From 5 kW to 100 kW that provide power for a small community or rural industry in remote areas away from the grid; and

» *Pico-hydro*: From a few hundred watts up to 5 kW (often used in remote areas away from the grid).

However, there is no agreed classification of "small" and "large" hydro and what constitutes "small" varies from country to country (Table 2.1). A given country's definition of what is a "small" hydropower system is often important because it can determine which schemes are covered by support policies for small hydro and which are covered by those (if any) for large hydro.

Table 2.1: Definition of small hydropower by country (MW)

	Small hydropower definition (MW)
Brazil	≤30
Canada	<50
China	≤50
European Union	≤20
India	≤25
Norway	≤10
Sweden	≤1.5
United States	5-100

Sources: IPCC, 2011 and IJHD, 2010.

Small hydropower plants are more likely to be run-of-river facilities than are large hydropower plants, but reservoir (storage) and run-of-river hydropower plants of all sizes utilise the same basic components and technologies.

The development of small hydropower plants for rural areas involves similar environmental, social, technical and economic considerations to those faced by large hydropower. Local management, ownership and community participation, technology transfer and capacity building are basic issues that will allow sustainable small hydropower plants to be developed. Small hydropower plants have been used to meet rural electrification goals in many countries. Currently there is 61 GW of small hydropower capacity in operation globally (Catanase and Phang, 2010). China has been particularly successful at installing small hydropower projects to meet rural electrification goals and 160 TWh was produced from 45 000 small hydro projects in China in 2010 (IN-SHP, 2010).

2.5 THE HYDROPOWER RESOURCE

The overall technical and economic potential for hydropower globally is available from some literature sources. However, the accuracy of these estimates is open to debate. In many cases country-level estimates of technical or economic potentials have been calculated using different criteria and combining these results means the totals are not directly comparable. Efforts to improve the mapping of the global hydropower resource are ongoing, but further work is required and should be encouraged.

However, taking into account these uncertainties, it is clear that the hydropower resource is very large, with many parts of the world being fortunate enough to have large resource potentials (Figure 2.4). Virtually all regions have some hydropower resources although these resources are sometimes concentrated in a small number of countries and are not always located adjacent to demand centres.

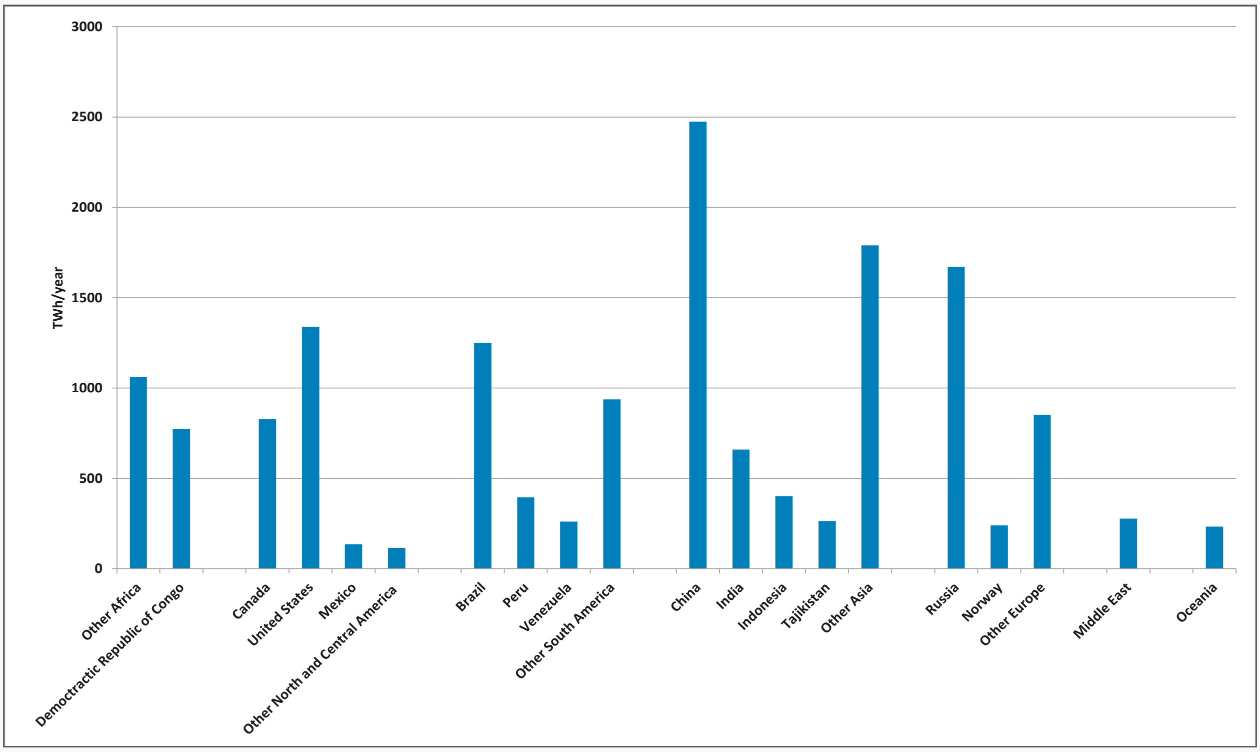

Figure 2.5: World hydropower technical resource potential[14] *Source: WEC, 2010.*

14 This is based on taking the theoretical total hydropower generation that could be achieved in a country by using all natural inflows as if they dropped to sea level and then assuming what proportion of this could technically be converted to hydropower with today's technologies. However, it is not known for certain whether all of the compiled data sources adhered to this methodology so the totals must be treated with caution.

Table 2.2: Hydropower resource potentials in selected countries

	Gross theoretical resource	Technically exploitable resource	Economically exploitable resource	Ratio of technical to economic
		(TWh)		
China	6 083	2 474	1 753	0.71
Russia	2 295	1 670	852	0.51
Brazil	3 040	1 250	818	0.65
Canada	2 067	827	536	0.65
India	2 638	660	442	0.67
United States	2 040	1 339	376	0.28
Tajikistan	527	264	264	1.00
Peru	1 577	395	260	0.66
Norway	600	240	206	0.86
Congo (Democratic Republic)	1 397	774	145	0.19
Venezuela	731	261	100	0.38
Indonesia	2 147	402	40	0.10
Mexico	430	135	33	0.24

Source: WEC, 2010.

The total technical hydropower resource potential depends on a number of critical assumptions in addition to average inflows into a catchment area. However, despite the uncertainty around the calculations, the estimated technical potential for hydropower is as much as 15 955 TWh/year or 4.8 times greater than today's production of hydropower. Estimates of the economically feasible hydropower capacity are not comprehensive enough to provide global estimates, but Table 2.2 presents data for a number of countries with important hydropower resources.

What the economically feasible hydropower potential is for a given country is a moving target. The cost of alternative generation options, which sets the limit at which the LCOE of a hydropower project would be economically feasible, as well as the costs of developing hydropower projects (e.g. through advances in civil engineering, cost reductions for equipment), will change over time. The simple analysis in Table 2.2 also highlights the limitations of some of the available data. The very high ratio of economic to technically feasible resources for some countries tends to suggest that only hydropower resources that have already been examined in detail have been included in the analysis. In other cases, the reason is that the country does have very economic hydropower resources.

Further work to better characterise the hydropower resource under standard definitions would help improve the comparability of resource estimates between countries and with other renewable power generation options. The efforts underway to achieve this should be encouraged.

Africa remains the region with the lowest ratio of deployment-to-potential, and the opportunities for growth are very large. However, in Africa complicated competing priorities and concerns mean that hydropower development is not straightforward.
The impact of hydropower development on local populations, their impacts on water use and rights, as well as issues over the biodiversity impacts of large-scale hydropower developments, mean that significant planning, consultation and project feasibility assessments are required. This is often required to take place in consultation with countries downstream, given the importance of Africa's rivers to the water supply of each country. Only once all major concerns are addressed can projects move to the detailed design phase and look to secure financing. The critical issue in Africa, and other regions, of the allocation of water rights between countries and different users within countries can be a significant delaying factor in getting project approval and funding. Growing populations and increasing water scarcity in some regions mean that these issues are complex and potentially divisive, but, without agreement, development is unlikely to move forward.

3. GLOBAL HYDROPOWER CAPACITY AND GENERATION TRENDS

3.1 CURRENT HYDROPOWER CAPACITY AND GENERATION

Hydropower is the largest source of renewable power generation worldwide. In 2009/2010 11 000 hydropower plants[15] in 150 countries were generating electricity. The total electricity generated by hydropower in 2009 reached 3 329 TWh, 16.5 % of global electricity production (Figure 3.1). This is around 85 % of total renewable electricity generation and provided more than one billion people with power (REN21, 2011 and IEA, 2011).

Global installed hydropower capacity was estimated to be between 926 GW and 956 GW in 2009/2010, excluding pumped storage hydropower capacity. Pumped hydro capacity was estimated to be between 120 GW and 150 GW (IHA, 2011) with a central estimate of 136 GW. In 2010, 30 GW of new hydro capacity was added (REN21, 2011 and BNEF, 2011). The global production of electricity from hydro was estimated to have increased by more than 5 % in 2010. This was driven by new capacity additions and above average hydro inflows in China (IHA, 2011). The world leaders in hydropower are China, Brazil, Canada, the United States and Russia. Together these countries account for 52 % of total installed capacity (Table 3.1)

Norway's generation system is almost 100 % hydro, with hydro accounting for 97 % of generation in 2009 and 99 % in 2010. In 2010, hydro accounted for 84 % of total generation in Brazil and 74 % in Venezuela. Central and South America generate nearly 64 % of all their electricity from hydropower (ANEEL, 2011). There are a number of countries in Africa that produce close to 100 % of their grid-based electricity from hydro. Russia has an

Table 3.1: Top ten countries by installed hydropower capacity and generation share, 2010

	Installed capacity (GW)		Hydropower's share of total generation (%)
China	210	Norway	99
Brazil	84	Brazil	84
USA	79	Venezuela	74
Canada	74	Canada	59
Russia	50	Sweden	49
India	38	Russia	19
Norway	30	India	18
Japan	28	China	16
France	21	Italy	14
Italy	20	France	8
Rest of world	302	Rest of world	14
World	936	World	16

Source: IHA, 2012 and IPCC, 2011.

15 *These plants contained an estimated 27 000 generating units.*

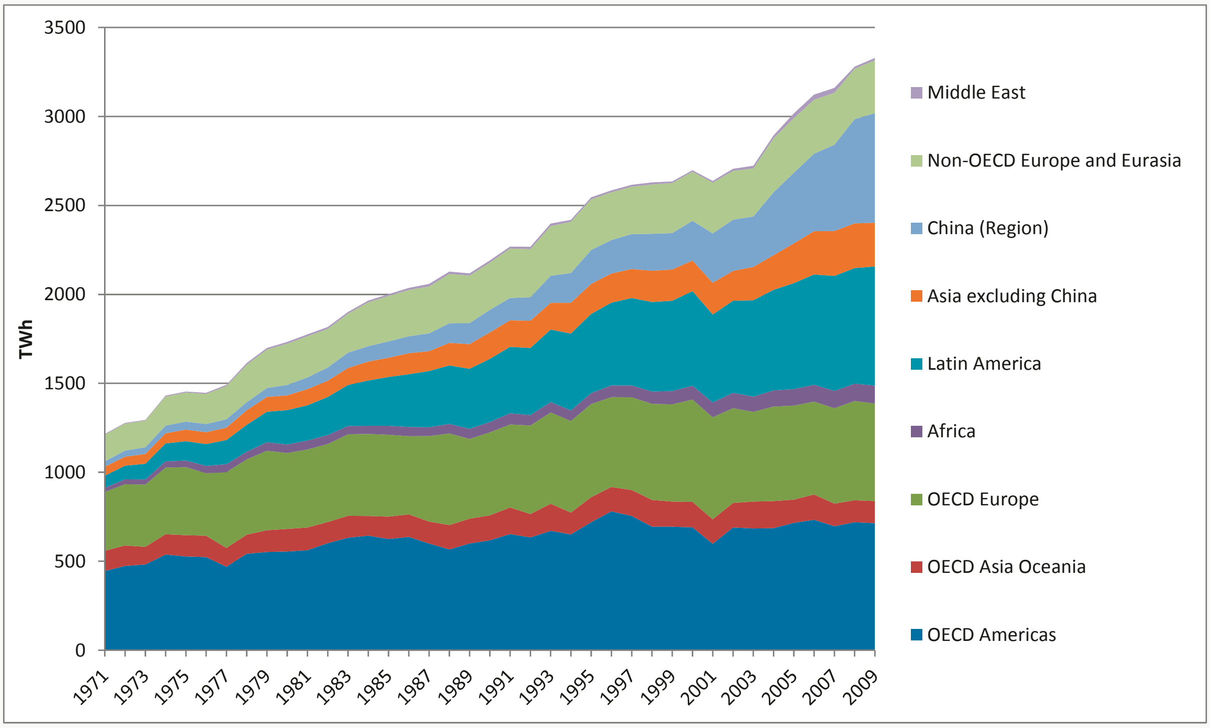

Figure 3.1: Hydropower generation by region, 1971 to 2009

Source: IEA.

estimated 50 to 55 GW of installed hydropower capacity, which represents about one-fifth of the country's total electric capacity (Frost and Sullivan, 2011).

Asia accounts for the largest share of global installed hydropower capacity, followed by Europe, then North and South America, then Africa (WEC, 2010 and IHA, 2011). China's installed hydropower capacity reached an estimated 210 GW in 2010, a significant increase over the 117 GW in operation at the end of 2005 (IHA, 2012 and US EIA, 2009). Despite having the largest installed capacity of hydropower plants in the world, only around 16 % to 17 % of China's total generation needs come from hydro. Hydropower in Africa currently accounts for some 32 % of current capacity, but this capacity is just 3 % to 7 % of the technical potential on the continent (IRENA, 2011).

3.2 THE OUTLOOK FOR HYDROPOWER

With less than one-quarter of the world's technical hydropower potential in operation, the prospects for growth in hydro capacity are good. However, long lead times, project design, planning and approval processes, as well as the time required to secure financing for these large multi-year construction projects, mean that capacity growth is more likely to be slow and steady than rapid.

The conventional hydropower activities focus on adding new generating capacity, improving the efficiency/capacity at existing hydroelectric facilities, adding hydroelectric generating capacity to existing non-powered dams and increasing advanced pumped-storage hydropower capacity.

Emerging economies in Asia (led by China) and Latin America (led by Brazil) have become key markets for hydropower development, accounting for an estimated 60 % of global activity (IHA, 2011). OECD economies in North America and Europe are focussing on the modernisation of existing facilities, often leading to increased capacity or generation capability, as well as new pumped storage facilities. However, new greenfield capacity is being added in relatively modest quantities.

China added 16 GW during 2010 to reach an estimated 210 GW of total hydro capacity. Brazil brought around 5 GW on stream in 2010, bringing its existing capacity to

81 GW while a further 8.9 GW is under construction (IHA, 2011 and IHA, 2012). In South America as a whole, 11 GW is planned and a further 16.3 GW is at the feasibility stage (IHA, 2012). In Western Asia, there is a total of 15.5 GW of capacity under construction with India accounting for 13.9 GW and Bhutan for 1.2 GW (IHA, 2012).

Canada added 500 MW of capacity in 2010, raising total installed hydropower capacity to 76 GW. However, the future should see higher rates of capacity coming on stream as more than 11 GW of new projects were under construction in Canada by early 2011. An estimated 1.3 GW of this is due to become operational before the end of 2012 (IHA, 2011 and REN 21, 2011). Canada has a total of 21.6 GW of hydropower capacity at different stages of planning or construction (IHA, 2012). Development in the United States has slowed recently due to the economic difficulties in North America. However, total installed capacity reached 78 GW in 2010 (to which must be added 20.5 GW of pumped storage), producing 257 TWh during the year, up from 233.6 TWh in 2009.

The largest projects completed in 2010 included the 1.1 GW Nam Theun 2 hydropower plant in Laos, China's 2.4 GW Jin'anqiao plant, Brazil's 0.9 GW Foz do Chapeco plant and two facilities (0.5 and 0.3 GW) in Ethiopia (IPCC, 2011).

Interest in pumped storage is increasing, particularly in regions and countries where solar PV and wind are reaching relatively high levels of penetration and/or are growing rapidly (IHA, 2011). The vast majority of current pumped storage capacity is located in Europe, Japan and the United States (IHA, 2011). About 4 GW of new pumped storage capacity was added globally in 2010, including facilities in China, Germany, Slovenia and the Ukraine. The central estimate of total pumped hydro capacity at the end of 2010 was approximately 136 GW, up from 98 GW in 2005 (IHA, 2011).

Worldwide, the installed capacity of small hydro is 61 GW (Catanase and Phang, 2010). Europe is a market leader in small hydropwoer technologies, and it is the second highest contributor to the European renewable energy mix. The European Commission's Renewable Energy Roadmap identifies small hydro power as an important ingredient in the EU's future energy mix.

China has ambitious plans that may not all be realised to start construction on 140 GW of capacity over the next five years (Reuters, 2011). In collaboration with Iran, China also plans to build the world's tallest dam, a 1.5 GW project in Iran's Zagros Mountains. Brazil plans two major projects in the Amazon region, including a 3.2 GW reservoir project due for completion in late 2011 (Hydro World, 2011). In North America and Europe, new plants are also under construction, but the focus is on modernising existing plants and adding pumped hydro storage capacity.

Long-term global scenarios for hydropower

A 2010 report from the International Energy Agency (IEA) projected that global hydropower production might grow by nearly 75% from 2007 to 2050 under a business-as-usual scenario, but that it could grow by roughly 85% over the same period in a scenario with aggressive action to reduce GHG emissions (IEA, 2010c). This is short of the IEA's assessment of the realistic potential for global hydropower, which is a two- to three-fold increase in generation over today's level. They estimate that the majority of the remaining economic development potential is located in Africa, Asia and Latin America (IEA, 2008 and IEA, 2010c). The IEA notes that, while small hydropower plants could provide as much as 150 GW to 200 GW of new generating capacity worldwide, only 5% of the world's small-scale hydropower potential has been exploited (IEA, 2008).

A review of the literature examining the potential contribution of renewable energy to climate change mitigation scenarios by the IPCC identified a median increase in the amount of hydropower generation of 35% by 2030 and 59% by 2050. However, the range of results in the scenarios examined was very wide, with the 25^{th} percentile of results indicating a 34% increase over 2009 by 2050, compared to a 100% increase for the 75^{th} percentile (IPCC, 2011).

4. THE CURRENT COST OF HYDROPOWER

Hydropower is a capital-intensive technology with long lead times for development and construction due to the significant feasibility, planning, design and civil engineering works required. There are two major cost components for hydropower projects:

- The civil works for the hydropower plant construction, including any infrastructure development required to access the site and the project development costs.
- The cost related to electro-mechanical equipment.

The project development costs include planning and feasibility assessments, environmental impact analysis, licensing, fish and wildlife/biodiversity mitigation measures, development of recreation amenities, historical and archaeological mitigation and water quality monitoring and mitigation.

The civil works costs can be broadly grouped into categories:

- Dam and reservoir construction;
- Tunnelling and canal construction;
- Powerhouse construction;
- Site access infrastructure;
- Grid connection;
- Engineering, procurement and construction (EPC); and
- Developer/owners costs (including planning, feasibility, permitting, etc.).

For developments that are far from existing transmission networks, the construction of transmission lines can contribute significantly to the total costs. Accessing remote sites may also necessitate the construction of roads and other infrastructure at the site.

The electro-mechanical equipment for the project includes the turbines, generators, transformers, cabling and control systems required. These costs tend to vary significantly less than the civil engineering costs, as the electro-mechanical equipment is a mature, well-defined technology, whose costs are not greatly influenced by the site characteristics. As a result, the variation in the installed costs per kW for a given hydropower project is almost exclusively determined by the local site considerations that determine the civil works needs.

There has been relatively little systematic collection of data on the historical trends of hydropower costs, at least in the publically available literature (IPCC, 2011). Such information could be compiled by studying the costs of the large number of already commissioned hydropower projects. However, because hydropower projects are so site-specific, it is difficult to identify trends. This would require detailed data on the cost breakdown of each project and require a significant investment in data collection, time and analysis. Until such time as analysis of this type is completed, it is therefore difficult to present historical trends in investment costs and the LCOE of hydropower.

4.1 TOTAL INSTALLED CAPITAL COSTS OF HYDROPOWER

The total investment costs for hydropower vary significantly depending on the site, design choices and the cost of local labour and materials. The large civil works required for hydropower mean that the cost of materials and labour plays a larger role in overall costs than for some other renewable technologies. There is significantly less variation in the electro-mechanical costs.

The total installed costs for large-scale hydropower projects typically range from a low of USD 1 000/kW to around USD 3 500/kW. However, it is not unusual to find projects with costs outside this range. For instance, installing hydropower capacity at an existing dam that was built for other purposes (flood control, water provision, etc.) may have costs as low as USD 500/kW. On the other hand, projects at remote sites, without adequate local infrastructure and located far from existing transmission networks, can cost significantly more than USD 3 500/kW.

Figure 4.1 summarises a number of studies that have analysed the costs of hydropower plants. A large, comprehensive cost analysis of over 2 155 potential hydropower projects in the United States totalling 43 GW identified an average capital cost of USD 1 650/kW, with 90 % of projects having costs below USD 3 350/kW (Hall, *et al.*, 2003). In another study (Lako et al., 2003), 250 projects worldwide with a total capacity of 202 GW had an average investment cost of just USD 1 000/kW and 90 % had costs of USD 1 700/kW or less (Lako et al., 2003).

Figure 4.2 presents the investment costs of hydropower projects by country. The cost of hydropower varies within countries and between countries depending on the resource available, site-specific considerations, cost structure of the local economy, etc., which explains the wide cost bands for hydropower. The lowest investment costs are typically associated with adding capacity at existing hydropower schemes or capturing energy from existing dams that do not have any hydropower facilities. The development of greenfield sites tends to be more expensive and typically range from USD 1 000 to USD 3 500/kW.

Small projects have investment costs in slightly higher range bands and are expected to have higher average costs. This is particularly true for plants with capacities of less than one MW where the specific (per kW) electro-mechanical costs can be very high and dominate total installed costs.

The investment costs per kW of small hydropower plant projects tend to be lower if the plant has higher head and installed capacity. The relationship between installed capacity and specific investment costs is strong irrespective of the head size. The economies of scale for head sizes above 25 to 30 metres are modest (Figure 4.3).

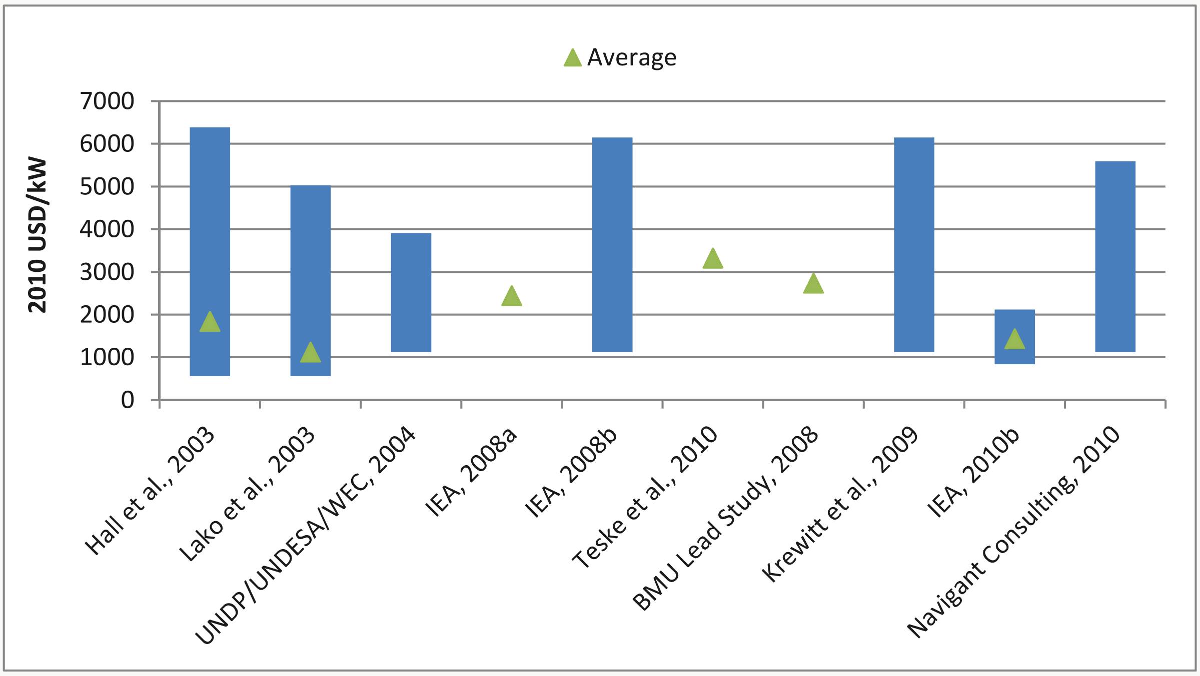

Figure 4.1: Summary of the installed costs hydropower projects from a range of studies

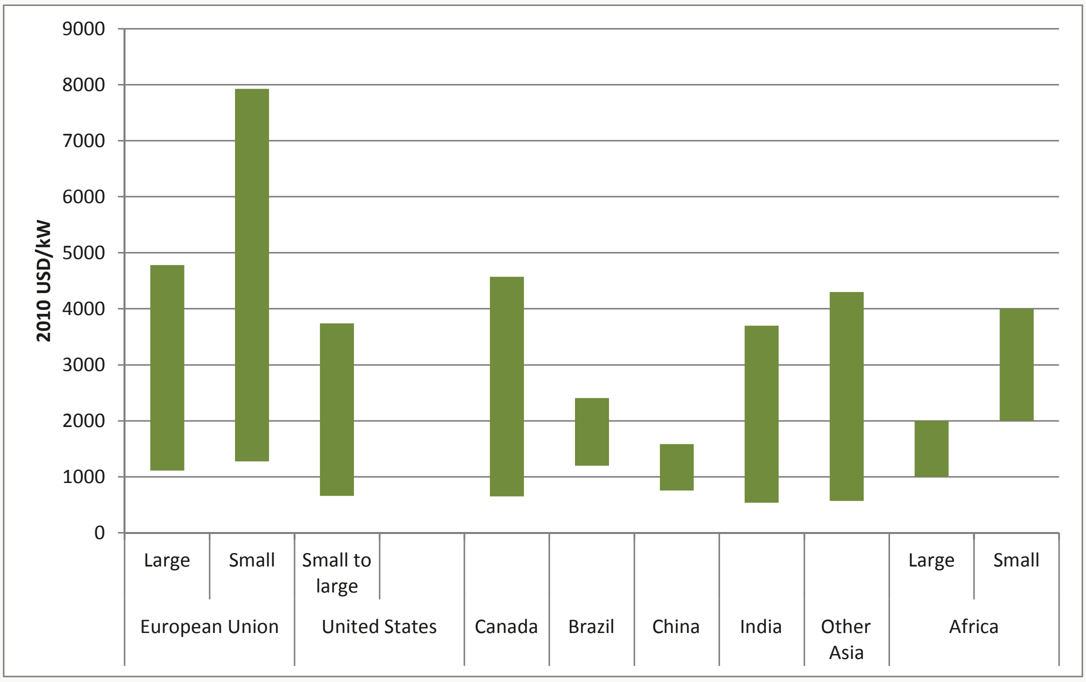

FIGURE 4.2: TOTAL INSTALLED HYDROPOWER COST RANGES BY COUNTRY

Sources: IRENA, 2011; IEA, 2010b; Black & Veatch, 2012; and IRENA/GIZ.

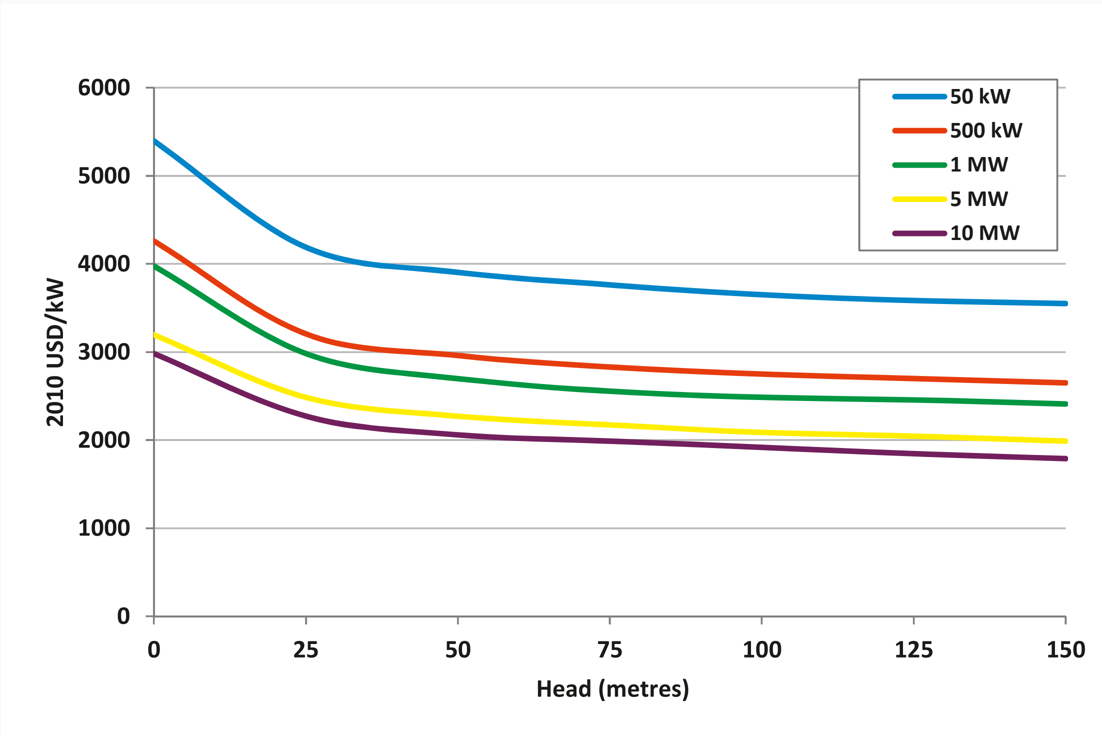

FIGURE 4.3: INVESTMENT COSTS AS A FUNCTION OF INSTALLED CAPACITY AND TURBINE HEAD

Source: Based on Kaldellis and Kondili, 2005.

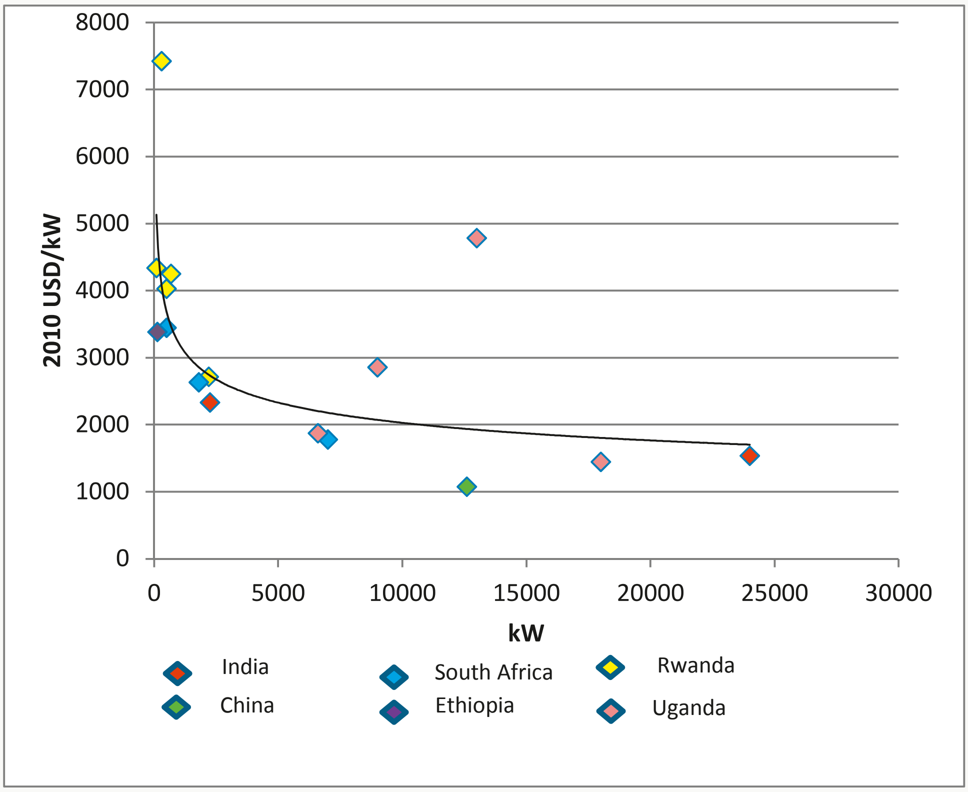

Figure 4.4: Installed capital costs for small hydro in developing countries by capacity

Source: IRENA/GIZ.

In the United Kingdom, plants between 1 MW and 7 MW have installed capital capital costs between USD 3 400 and USD 4 000/kW (Crompton, 2010). However, plants below 1 MW can have significantly higher capital costs. The range can be from USD 3 400 to USD 10 000/kW, or even more for pico-hydropower projects.

Data for small hydro in developing countries from an IRENA/GIZ survey and from other sources highlight similar cost bands (Figure 4.4), although they suggest that larger small hydro projects in developing countries may have slightly lower specific costs. Critically, mini- and pico-hydro projects still appear to generally have costs below those of PV systems, suggesting that small hydros' role in off-grid electrification will remain a strong one.

For large hydropower plants, economic lifetimes are at least 40 years, and 80-year lifetimes can be used as upper bound. For small-scale hydropower plants, the typical lifetime is 40 years but in some cases can be less. The economic design lifetime may differ from actual physical plant lifetimes.

Refurbishment, repowering and rehabilitation of existing hydropower plants

Hydropower plant refurbishment, repowering and rehabilitation (hereafter referred to as "refurbishment" for simplicity) refer to a range of activities such as repair or replacement of components, upgrading generating capability and altering water management capabilities. Most refurbishment projects focus on the electro-mechanical equipment, but can involve repairs or redesigns of intakes, penstocks and tail races.

Generally speaking, the output of a hydropower scheme will decline over time as equipment and some of the civil works become worn down by the flow of water or constant use. At a certain point, it will often become economic to refurbish the plant to reduce the increasing O&M costs and restore generation capacity to its designed level, or even take the opportunity to boost it above this original level.

Refurbishment projects generally fall into two categories:

- *Life extension* is where equipment is replaced on a "like for like" basis and little effort is made to boost generating capacity potential from what it was. This will, however, generally result in increased generation relative to what was being produced at the scheme as worn out equipment is replaced. On average, these repairs will yield a 2.5 % gain in capacity; and

- *Upgrades* are where increased capacity and, potentially, efficiencies are incorporated into the refurbishment, where the increased cost can be justified by increased revenues. These upgrades can be modest or more extensive in nature and depending on the extent of the wear and tear and additional civil works to try and capture more energy yield increases in capacity of between 10 % and as much as 30 %.

The slowing in the development of greenfield projects in countries that have exploited most of their existing potential and the many countries with ageing hydropower projects mean that refurbishment will become an increasingly important way of boosting hydropower output and adding new capacity.

The rehabilitation and refurbishment of old hydropower plants will usually become economic at a certain point, as the reduced O&M costs and higher output post-refurbishment will offset what are the relatively modest low investment costs for refurbishment. In addition, the current R&D efforts into rehabilitation and refurbishment of hydropower plants include the development of innovative technologies to minimise their environmental impact.

For small hydropower plant, ambitious refurbishments can be envisaged. It may be possible to completely rebuild the hydropower scheme by constructing a new plant, completely replacing the main components and structures to capture more energy. The refurbishment of large hydropower schemes will generally aim to extend the plant's working lifespan, improve the yield, increase in reliability, reduce maintenance needs and increase the degree of automation of operations.

The key items that need to be replaced or repaired are the turbines, which can suffer from pitting, wear or even fatigue cracks. Similarly, in the generator, stator windings last for as much as 45 years, but will eventually benefit from replacement. The generator rotor and bearings could also need replacement. In addition to the electro-mechanical components, repairs or redesigns of intakes, penstocks and the other civil works can be considered in order to improve efficiency and increase electricity generation.

The data available on the costs of refurbishment isn't extensive, however, studies of the costs of life extension and upgrades for existing hydropower have estimated that life extensions cost around 60 % of greenfield electro-mechanical costs and upgrades anywhere up to 90 % depending on their extent (Goldberg and Lier, 2011).

4.2 BREAKDOWN OF HYDROPOWER COSTS BY SOURCE

The cost breakdown of an indicative 500 MW new greenfield hydropower project in the United States is presented in Figure 4.5. The reservoir accounts for just over one-quarter of the total costs, while tunnelling adds another 14 %. The powerhouse, shafts and electro-mechanical equipment together account for 30 % of the total costs. The long lead times for these types of hydropower projects (7-9 years) mean that owner costs (including the project development costs) can be a significant portion of the overall costs.

The largest share of installed costs for large hydropower plant is typically taken up by civil works for the construction of the hydropower plant (such us dam, tunnels, canal and construction of powerhouse, etc.). Electrical and mechanical equipment usually contributes less to the cost. However, for hydropower projects where the installed capacity is less than 5 MW, the costs of electro-mechanical equipment may dominate total costs due to the high specific costs of small-scale equipment.

The cost breakdown for small hydro projects in developing countries reflects the diversity of hydropower projects and their site-specific constraints and opportunities (Figure 4.6). The electro-mechanical equipment costs tend to be higher than for large-scale projects, contributing from 18 % to as much as 50 % of

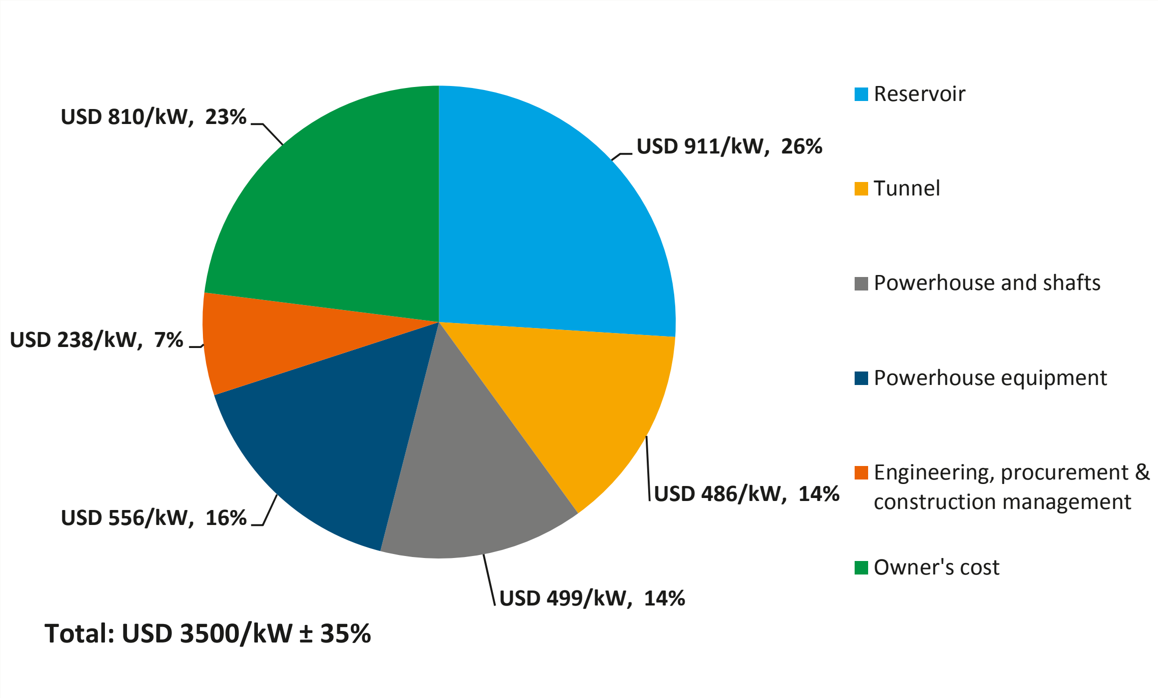

Figure 4.5: Cost breakdown of an indicative 500 MW greenfield hydropower project in the United States

Source: Black and Veatch, 2012.

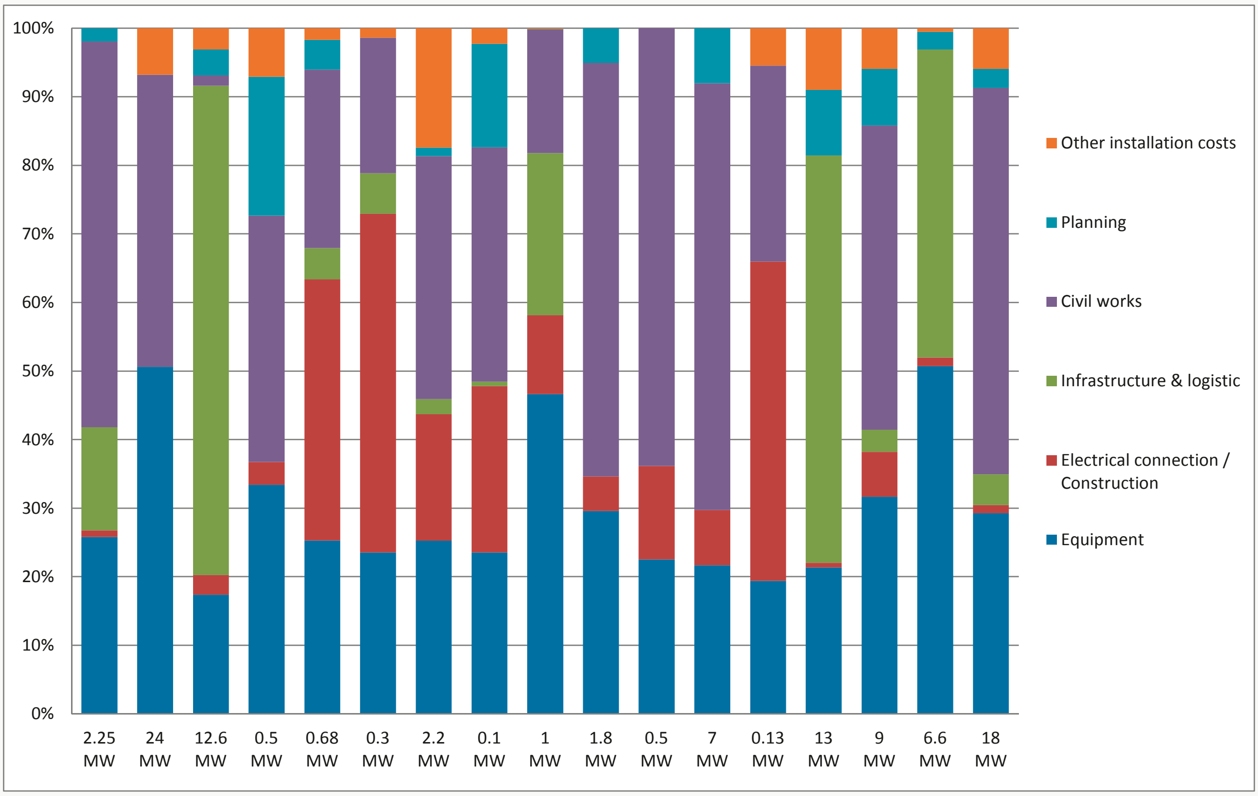

Figure 4.6: Cost breakdown for small hydro projects in developing countries

Source: IRENA/GIZ.

total costs. For projects in remote or difficult to access locations, infrastructure costs can dominate total costs.

The contribution of civil works to capital costs

For large hydropower projects, the capital costs are dominated by the civil works. The cost of civil works is influenced by numerous factors pertaining to the site, the scale of development and the technological solution that is most economic. Hydropower is a highly site-specific technology where each project is a tailor-made outcome for a particular location within a given river basin to meet specific needs for energy and water management.

Around three-quarters of the total investment costs of hydropower projects are driven by site-specific elements that impact the civil engineering design and costs. Proper site selection and hydro scheme design are therefore key challenges (Ecofys, *et al.*, 2011). Therefore, proper dimensioning and optimisation of the key elements of civil structures and streamlining construction work during the engineering design and implementation stages are important factors to reduce construction costs of large-scale projects.

The site-specific factors that influence the civil construction costs include hydrological characteristics, site accessibility, land topography, geological conditions, the construction and design of the hydropower plant and the distance from existing infrastructure and transmission lines. The cost of the civil works for the hydropower plant will also depend on commodity prices and labour costs in the country. The cost of civil works in developing countries is sometimes lower than in developed countries due to the use of local labour. However, this is not always the case as poorer infrastructure or remote sites will entail significant additional costs. Similarly, cement and steel prices are sometimes higher in developing countries.

Electro-mechanical equipment costs

The electro-mechanical equipment used in hydropower plants is a mature technology, and the cost is strongly correlated with the capacity of the hydropower plant. The proposed capacity of a hydropower plant can be achieved by using a combination of a few large turbines or many small turbines and generating units. This will be influenced to some extent by the hydro resource but is also a trade-off between guaranteeing availability (if there is only one generator and it is offline, then generation drops to zero) and the capital costs (smaller units can have higher costs per kW). The design decision is therefore a compromise between trying to minimise capital costs and maximise efficiency and the number of generating units to ensure the best availability.

A range of studies have analysed the cost of the electro-mechanical equipment for hydro plants as a function of total plant size and head.[16] Recent work has looked at using the following formula to describe the relationship between costs and the power and head of a small hydropower scheme (Ogayar and Vidal, 2009):

$$\text{COST (per kW)} = \alpha P^{1-\beta} H^{\beta 1}$$

Where:

P is the power in kW of the turbines;

H is the head in metres;

α is a constant; and

β and $\beta 1$ are the co-efficients for power and head, respectively.

The results from analysis using this cost estimation methodology is available for a range of developed countries, but most of these studies are ten years old or more. The recent analysis of small hydropower plants in Spain which analysed separately the costs for Pelton, Francis, Kaplan, and semi-Kaplan turbines yielded equations a good fit (Ogayar and Vidal, 2009).

The results yielded by these types of analysis have been checked against existing cost data for electro-mechanical equipment from global manufacturers (Alstom, Andritz, Gilbert Gilkes & Gordon Ltd, NHT and Voith Siemens) and were found to be statistically consistent with real cost data from existing plants. Although this type of analytical

16 See Ogayar and Vidal (2009) for some of these studies.

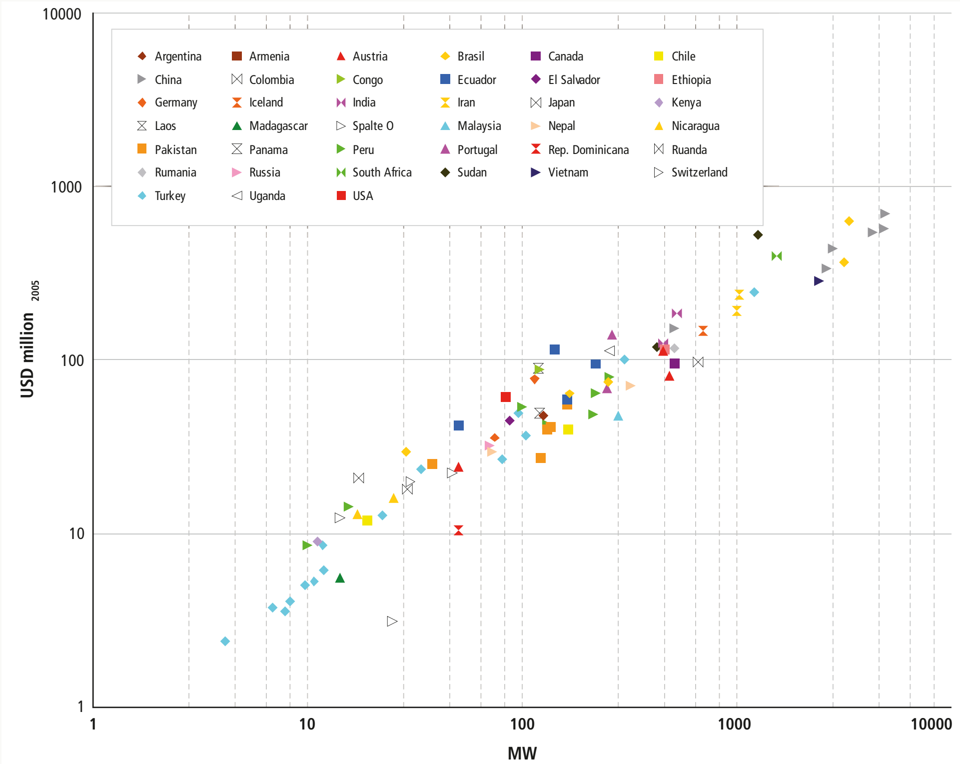

Figure 4.7: Electro-mechanical equipment for hydro as a function capacity by country (log-scale)

Source: Alvarado-Ancieta, 2009.

approach is a useful first order estimate of costs, the results need to be treated with caution, given the range of costs experienced in the real world (Figure 4.7).

4.3 OPERATION AND MAINTENANCE COSTS

Once commissioned, hydropower plants usually require little maintenance, and operation costs will be low. When a series of plants are installed along a river, centralised control and can reduce O&M costs to very low levels.

Annual O&M costs are often quoted as a percentage of the investment cost per kW per year. Typical values range from 1% to 4%. The IEA assumes 2.2% for large hydropower and 2.2% to 3% for smaller projects, with a global average of around 2.5% (IEA, 2010c). Other studies (EREC/Greenpeace, 2010 and Krewitt, 2009) indicate that fixed O&M costs represent 4% of the total capital cost. This figure may be appropriate for small-scale hydropower, but large hydropower plants will have values significantly lower than this. An average value for O&M costs of 2% to 2.5% is considered the norm for large-scale projects (IPCC, 2011 and Branche, 2012). This will usually include the refurbishment of mechanical and electrical equipment like turbine overhaul, generator rewinding and reinvestments in communication and control systems.

However, it does not cover the replacement of major electro-mechanical equipment or refurbishment of penstocks, tailraces, etc. The advantage of hydropower is that these kinds of replacements are infrequent and design lives of 30 years or more for the electro-mechanical equipment and 50 years or more for the refurbishment of penstocks and tail races are normal.

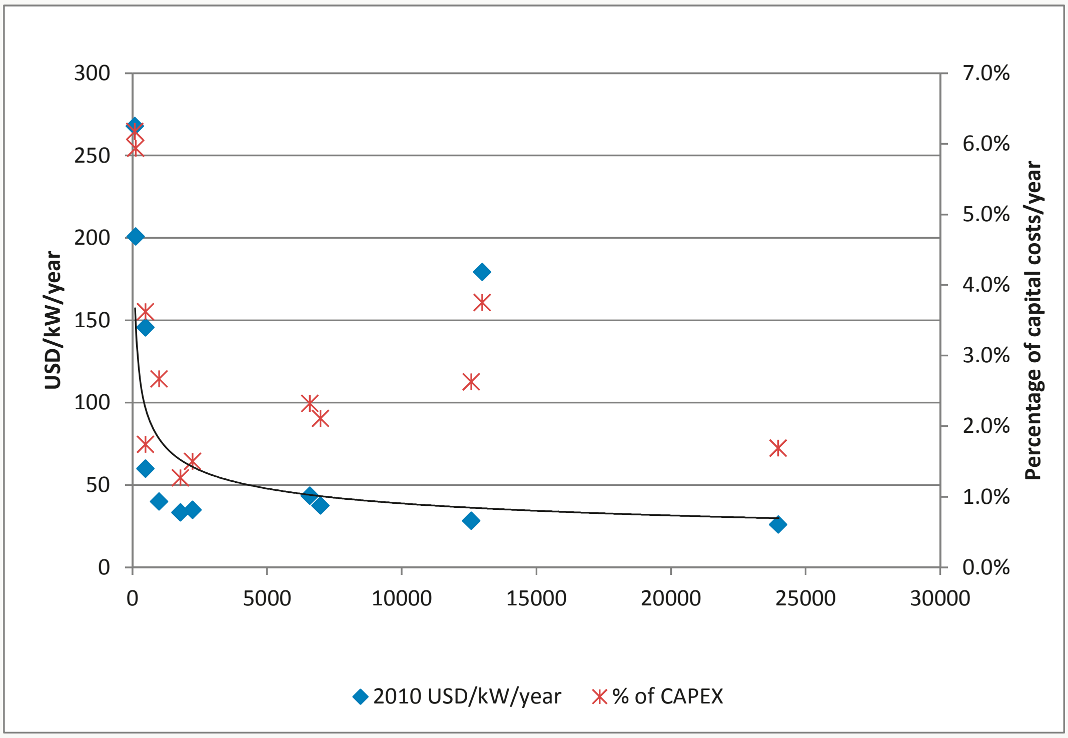

Figure 4.8: Operations and maintenance costs for small hydro in developing countries

Source: IRENA/GIZ.

A recent study indicated that O&M costs averaged USD 45/kW/year for large-scale hydropower projects and around USD 52/kW/year for small-scale hydropower plants (Ecofys et al., 2011). These figures are not inconsistent with the earlier analyses.

These values are consistent with data collected by IRENA and GIZ for small hydropower projects in developing countries (Figure 4.8). Average O&M costs for mini- and pico-hydro projects can be significantly above the average, given the economies of scale available for O&M costs at hydropower projects.

5. COST REDUCTION POTENTIALS

Hydropower is a mature, commercially proven technology and there is little scope for significant cost reductions in the short-to-medium term. Technological innovation could lower the costs in the future, although this will mainly be driven by the development of more efficient, lower cost techniques in civil engineering and works. These improvements and cost reductions in major civil engineering techniques (tunnelling, construction, etc.) could help to reduce hydropower investment costs below what they otherwise would be.

However, analysis of cost reduction potentials in the literature does not provide a clear picture of any likely trends. Some studies expect slight increases in the range of installed costs, while others expect slight decreases when looking out to 2030 or 2050 (EREC/ Greenpeace, 2010; IEA, 2008a; IEA, 2008b; IEA, 2010c; and Krewitt et al., 2009). Part of the problem is that it is difficult to separate out improvements in civil engineering techniques that may reduce costs (which would lower the supply curve) and the fact that the best and cheapest hydropower sites have typically already been exploited (i.e. we are moving up and along the supply curve). As a consequence of these difficulties, the inconclusive evidence from the literature and the fact that hydropower is a mature technology; no material cost reductions for hydropower are assumed in the period to 2020 in the analysis presented in this paper.

6. THE LEVELISED COST OF ELECTRICITY FROM HYDROPOWER

Hydropower is a proven, mature, predictable technology and can also be low-cost. It requires relatively high initial investments but has the longest lifetime of any generation plant (with parts replacement) and, in general, low operation and maintenance costs. Investment costs are highly dependent on the location and site conditions, which determine on average three-quarters of the development cost (Ecofys, *et al.*, 2011). The levelised cost of electricity for hydropower plants spans a wide range, depending on the project, but under good conditions hydropower projects can be very competitive.

Existing hydropower plants are some of the least expensive sources of power generation today (IEA, 2010b). However, there is a wide range of capital costs and capacity factors that are possible, such that the LCOE of hydropower is very site-specific. The critical assumptions required to calculate the LCOE of hydropower are the:

- Installed capital cost;
- Capacity factor;
- Economic life;
- O&M costs; and
- The cost of capital.

The cost of capital (discount rate) assumed to calculate the LCOE is 10 %.[17] The other assumptions have been sourced from the earlier sections of this paper.

There is insufficient information on the LCOE trends for hydropower, in part due to the very site-specific nature of hydropower projects and the lack of time series data on investment costs. Investment costs vary widely from a low of USD 450/kW to as much as USD 6 000/kW or more. Another complicating factor is that it is possible to design hydropower projects to perform very differently. Capacity can be low to ensure high average capacity factors, but at the expense of being able to ramp up production to meet peak demand loads. Alternatively, a scheme could have relatively high capacity and low capacity factors, if it is designed to help meet peak demands and provide spinning reserve and or/or other ancillary grid services.

The decision about which strategy to pursue for any given hydropower scheme is highly dependent on the local market, structure of the power generation pool, grid capacity/constraints, the value of providing grid services, etc. More than perhaps any other renewable energy, the true economics of a given hydropower scheme will be driven by these factors, not just the amount of kWh's generated relative to the investment. Hydropower is uniquely placed to capture peak power prices and the value of ancillary grid services, and these revenues can have a large impact on the economics of a hydropower project.[18]

6.1 RESULTS FROM STUDIES OF THE LCOE OF HYDROPOWER

Black & Veatch studied the cost of new renewable electricity generation in the western United States

17 This discount rate is the same as used in the four other renewable power generation costing papers on wind, biomass, solar PV and concentrating solar power.

18 It is beyond the scope of this report to try to quantify these benefits, but these are thought to add anywhere between USD 0.01 and USD 0.05/kWh in value, and, in certain cases, it could be even more.

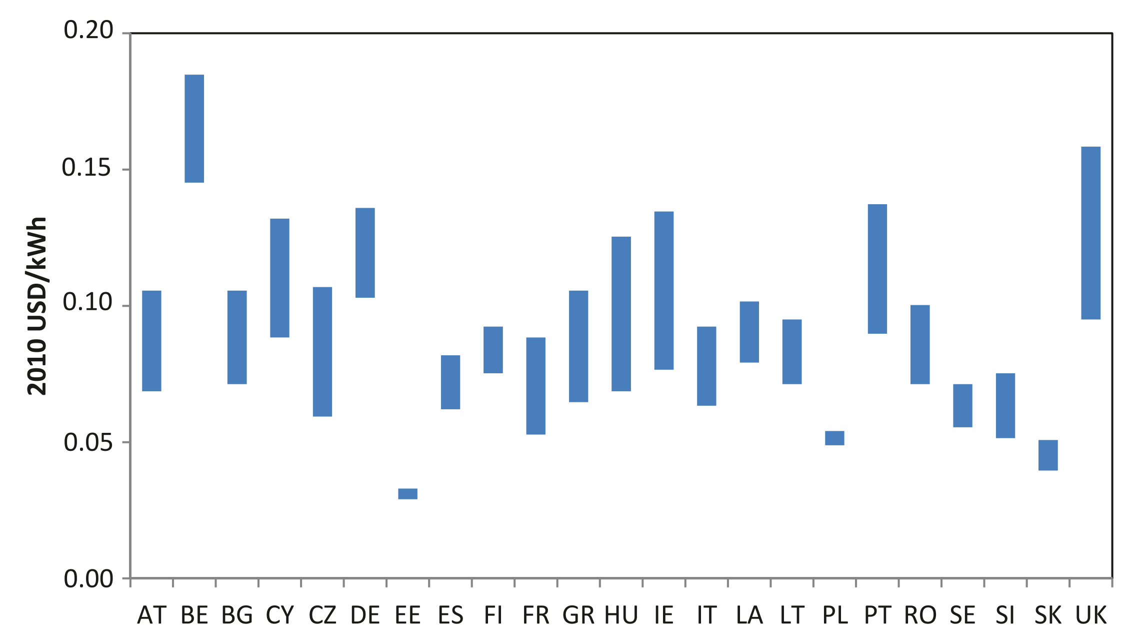

Figure 6.1: The minimum to average levelised cost of electricity for small hydropower in the European Union
Note: Country abbreviations are the EU standard.[19]

Source: Ecofys, et al., 2011.

(where much of the potential for new hydropower in the United States is located) and estimated that the LCOE of new hydropower capacity was in the range of USD 0.02/kWh to USD 0.085/kWh, with the lowest costs being for additional capacity at existing hydropower schemes (Pletka and Finn, 2009). This compares with earlier analysis that put the cost range at USD 0.018 to USD 0.13/kWh for new capacity at existing hydroelectric schemes and between USD 0.017 and USD 0.20/kWh for new greenfield hydropower schemes (WGA, 2009).

The LCOE of small hydropower in Europe, where most of the exploitable large-scale projects have already been constructed, reveals a wide range, depending on the local resource and cost structure, and ranges from a low of USD 0.03 to USD 0.16/kWh. The average cost for European countries ranges from USD 0.04 to USD 0.18/kWh (Figure 6.1).

A brief review of the LCOE range for hydropower in countries with the largest installed capacity of hydropower today is revealing. At the best sites, the LCOE of hydro is very competitive and among the lowest cost generation options available. However, the majority of new developments will be in less optimal sites than existing hydropower schemes, although this is not always the case. The average LCOE of new developments is more likely to fall somewhere in the middle of the estimated LCOE range presented in Figure 6.2.

The incorporation of small hydropower in the analysis for the United States, Canada and Africa can have a big impact on the range of potential costs. Although small hydro can be a competitive solution for remote locations, its LCOE will tend to be higher than an equivalent large-scale project. Similarly, at the lower end of the range, the incorporation of upgrading projects or the development of hydropower schemes at existing dams without a current hydropower scheme can suggest that hydropower costs are very low, when these tend to be relatively limited opportunities to add new capacity.

Figure 6.3 presents the LCOE of 2 155 hydropower projects plotted against their cumulative capacity that were evaluated in the United States. These represent undeveloped sites, existing dams without hydropower

19 See http://publications.europa.eu/code/en/en-370100.htm

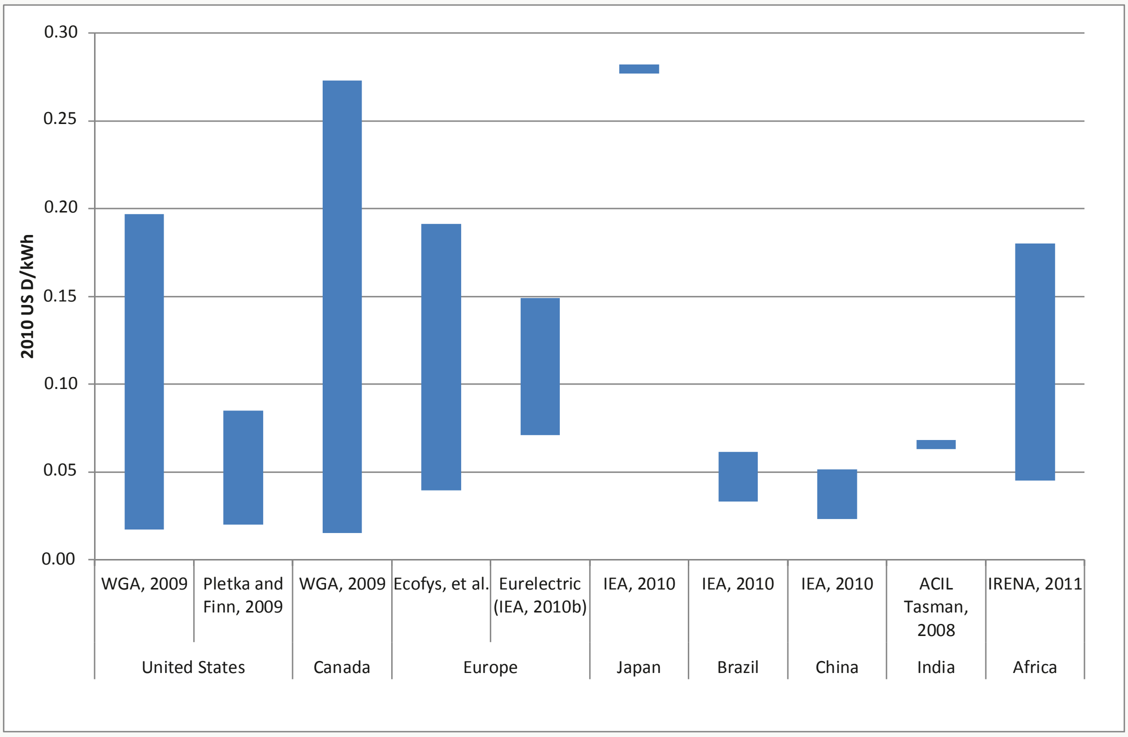

Figure 6.2: Levelised cost of electricity for hydropower plants by country and region
Note: Assumptions on capital costs, capacity factors, O&M costs, lifetimes and discount rates differ. Refer to each study for the details.

Sources: ACIL Tasman, 2008; Ecofys, et al., 2011; IEA, 2010b; IRENA, 2011; Pletka and Finn, 2009; and WGA, 2009.

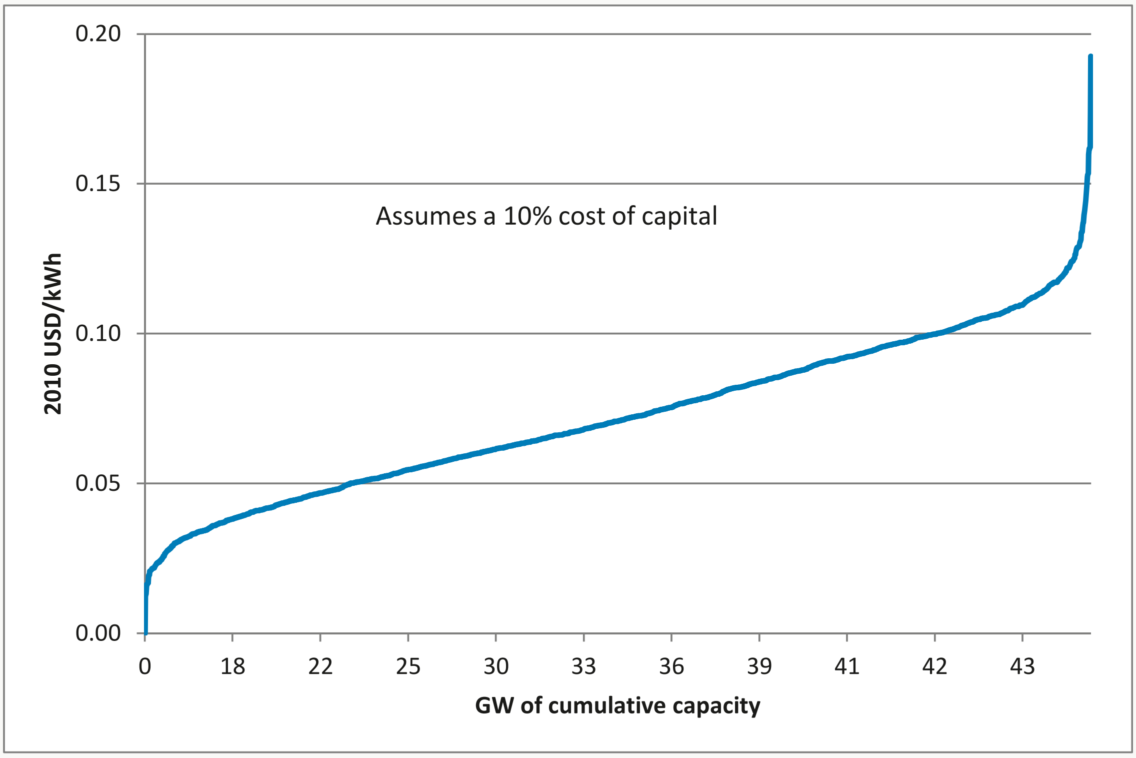

Figure 6.3: The LCOE of hydropower in the United States

Source: Hall, 2003 and IRENA.

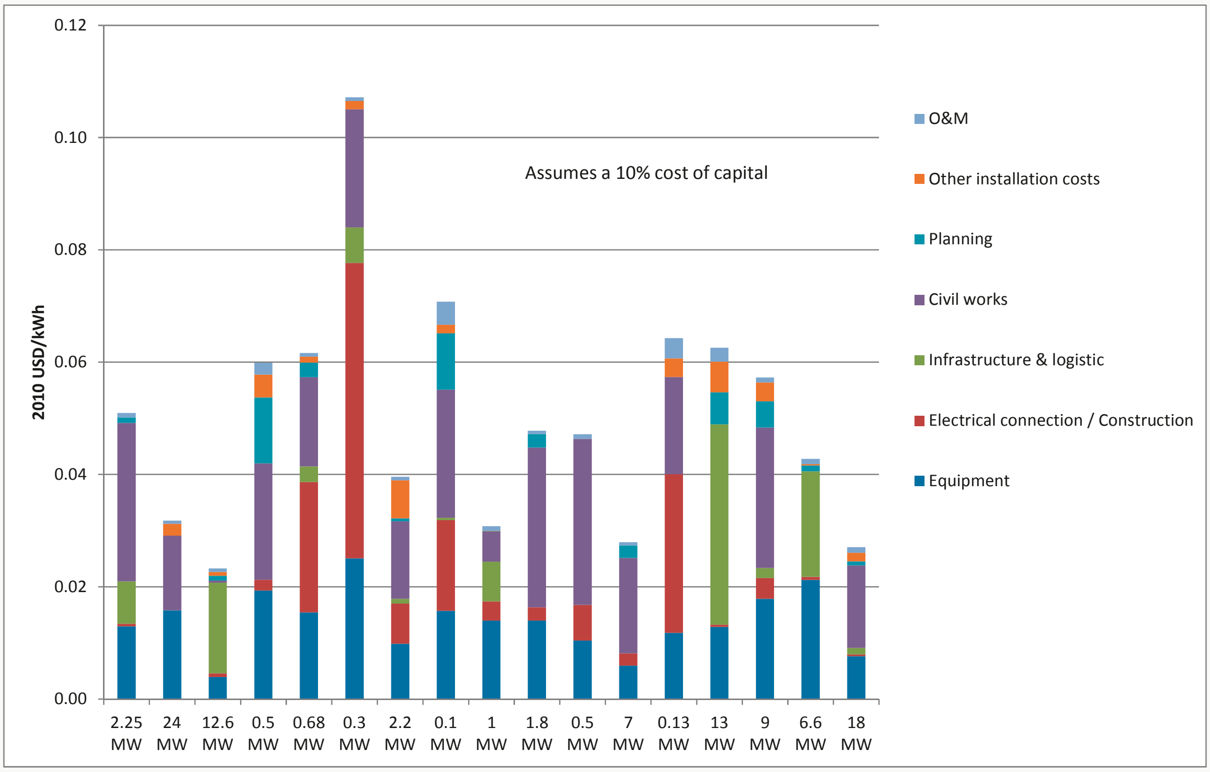

Figure 6.4: The LCOE of small hydropower for a range of projects in developing countries

Source: IRENA/GIZ.

and the expansion of existing hydropower schemes (Hall, 2003). The database includes cost estimates for the capital costs (civil works, electro-mechanical costs, etc.), licensing and mitigation costs to address archaeological, fish and wildlife, recreation or water quality monitoring requirements.[20]

Around 40 % of the capacity studied would come from undeveloped sites, 48 % from existing dams without hydropower schemes and the remainder from expansions at existing hydropower schemes. The average installed cost is USD 1 800/kW with an average capacity factor 52 %. Fixed O&M costs average around USD 10/kW/year while variable O&M costs average USD 0.002/kWh.

The LCOE of the projects evaluated ranged from a low of just USD 0.012/kWh for additional capacity at an existing hydropower project to a high of USD 0.19/kWh for a 1 MW small hydro project with a capacity factor of 30 %. The weighted average cost of all the sites evaluated was USD 0.048/kWh. The LCOE of 80 % of the projects was between USD 0.018 and USD 0.085/kWh.

Figure 6.4 presents the LCOE of small hydropower projects in developing countries, broken down by source. The LCOE of small hydropower projects ranges from a low of USD 0.023/kWh to a high of USD 0.11/kWh. The share of O&M in the LCOE of the hydropower projects examined ranges from 1% to 6 %. The largest share of the LCOE is taken up by the costs for the electro-mechanical equipment and the civil works.

The share of the electro-mechanical equipment in the total LCOE ranged from a low of 17 % to a high of 50 %, with typical values being in the range 21% to 31%. The civil works had the highest contribution to the total LCOE in nine of the projects examined and their share ranged from zero (for an existing dam project) to a high of 63 %. In some remote projects, grid connection and electrical infrastructure dominated while it was significant in a number of projects without being dominant. Similarly, infrastructure and logistical costs can be a significant contributor to overall costs where site access is difficult and/or far from existing infrastructure.

20 The capital and O&M costs were not estimated using detailed, site-specific engineering analysis of the projects, but with capital and O&M tools developed for the project. The actual costs would vary around these estimates.

6.2 HYDROPOWER LCOE SENSITIVITY TO THE DISCOUNT RATE

Given that hydropower is capital-intensive, has low O&M costs and no fuel costs, the LCOE is very sensitive to investment costs and interest rates but less sensitive to lifetime, given the lifetime range typical for hydropower.

The sensitivity of the LCOE of hydropower to different discount rates (3 %, 7 %, 10 %) and lifetimes (40 and 80 years) (IPCC, 2011) is presented in Table 6.1. The LCOE of hydropower projects is not particularly sensitive to assumptions about their economic lifetimes because they are so long. However, because virtually all of the costs are upfront capital costs, the LCOE is very sensitive to the discount rate used. The difference between a 3 % discount rate and a 10 % discount rate is very significant, with the LCOE increasing by between 85 % and 90 % as the discount rate increases from 3 % to 10 %.

Table 6.1: Sensitivity of the LCOE of hydropower projects to discount rates and economic lifetimes

Investment cost (USD/kW)	Discount rate (%)	LCOE (US cents/kWh)	Lifetime (years)	LCOE (US cents/kWh)
1 000	3	1.7	80	1.5
1 000	7	2.5	80	2.4
1 000	10	3.2	80	3.2
2 000	3	3.5	80	2.9
2 000	7	5.1	80	4.8
2 000	10	6.5	80	6.3
3 000	3	5.2	80	4.4
3 000	7	7.6	80	7.3
3 000	10	9.7	80	9.5

Note: base case assumes an economic life of 40 years, a 45 % capacity factor and 2.5 % of capital costs per year for O&M.
Source: IPCC, 2011.

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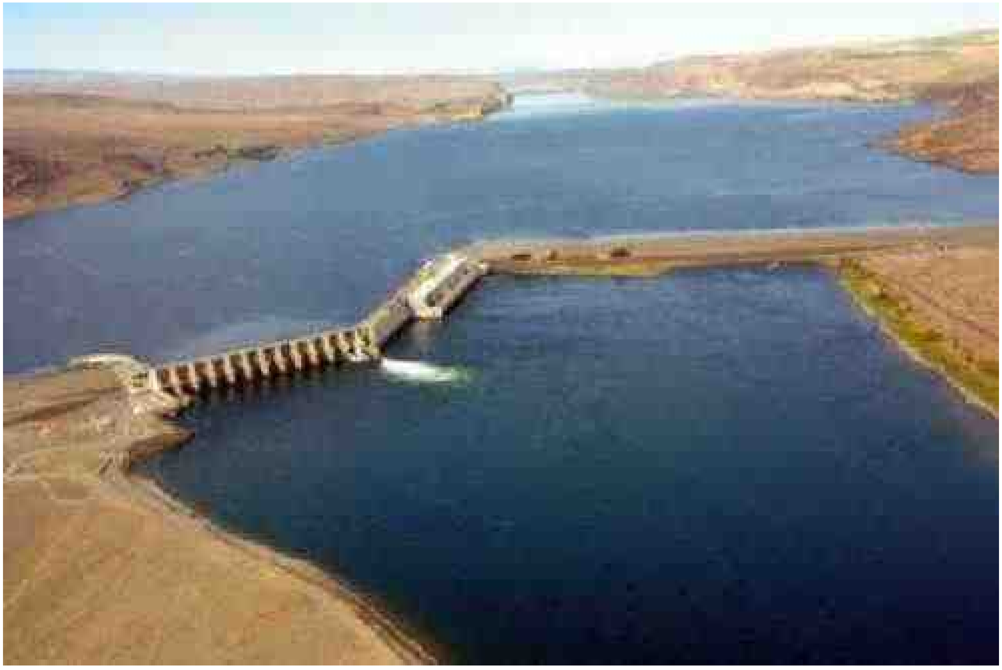

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