Sustainable Energy Handbook

Module 4.1

Hydroelectricity

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1 General Introduction

An important source of alternative energy is hydropower which broadly converts the flow of rivers and ocean waves and tides into electricity through dams and turbines. The highly interesting characteristic of these water sources is that they are fully renewable and free of charge.

Most countries on continents worldwide have harnessed a significant part of this resource except Africa which is lagging behind with only 8% of its technically and economically feasible potential.

At a time when fossil fuels prices are still high, developing and implementing hydropower projects is a competitive alternative. However, as water resources are a public good belonging to the community and very often shared by several nations, the design of hydropower schemes must be carefully prepared in compliance with national and international laws and respectful of the interests of riparian communities.

The nature of hydropower schemes generally comprising civil works of significant dimensions involving disturbance to natural sites requires a careful evaluation, mitigation and fair compensation of impacts to the environment, populations, natural habitats and cultural and religious assets.

Despite such schemes are of capital intensive nature requiring large amounts of funds at the time of their construction, their further operating costs are quite low compared to other power generation technologies.

The design of hydropower schemes is highly complex and time consuming. It requires extensive investigations and surveys in many technical domains including geology, seismology, topography, hydrology, geotechnical, construction material engineering, electro-mechanical and electrical engineering and much more.

2 General principles

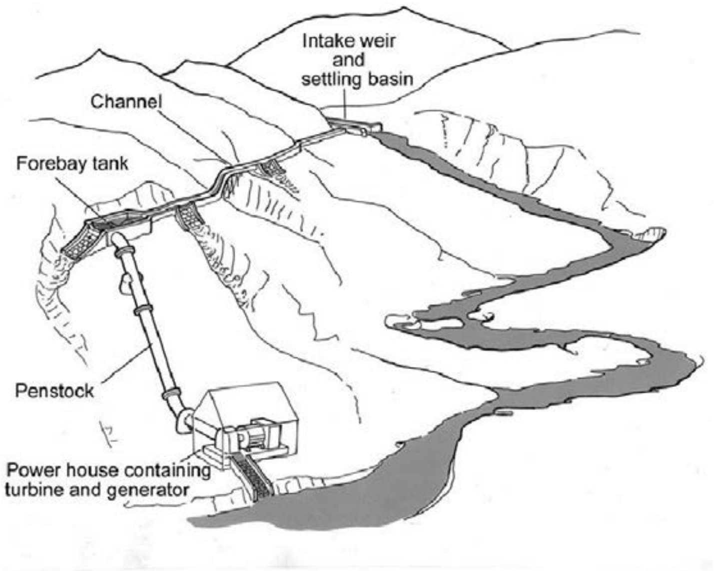
By the law of gravity, all rivers and streams flow downhill across the land surface. This motion which is a form of kinetic energy can be converted into electricity when it is forced to flow through turbines coupled to electric generators. The "turbined" water can be drawn directly from the river for run-of-the river schemes or from a reservoir where water is stored behind a dam for use on demand. These two types of schemes are the most frequently developed, depending on the topographical, hydrological and river regimes patterns at the site.

A typical hydro generating station can be described under two main headings: civil works and electro/mechanical equipment as illustrated in the figure below.

The main civil works of a hydro scheme development are the diversion dam or weir, the water passages and the powerhouse. The diversion dam or weir directs the water into a canal, tunnel, penstock or turbine inlet. The water then passes through the turbine, spinning it with enough force to create electricity through a generator. The water then flows back into the river via a tailrace.

The primary electrical and mechanical components of a small hydro plant are the turbine(s) and the generator(s). A number of different types of turbines have been designed to cover the broad range of hydropower site conditions found around the world. The type of turbine is selected depending on the available head.

Figure 1: Illustration showing the components of a hydropower plant.



Photos of a small existing power plant showing 1) the power house, the penstock, the transformer and the evacuation overhead line 2) the weir creating the head.

3 Technology overview

Turbines used for **low to medium head** applications are usually of the reaction type and include Francis and fixed and variable pitch (Kaplan) propeller turbines. The runner or turbine "wheel" of a reaction turbine is completely submersed in water. Turbines used for **high-head** applications are generally referred to as impulse turbines. Impulse turbines include the Pelton and crossflow designs. The runner of an impulse turbine spins in the air and is driven by a high-speed jet of water.

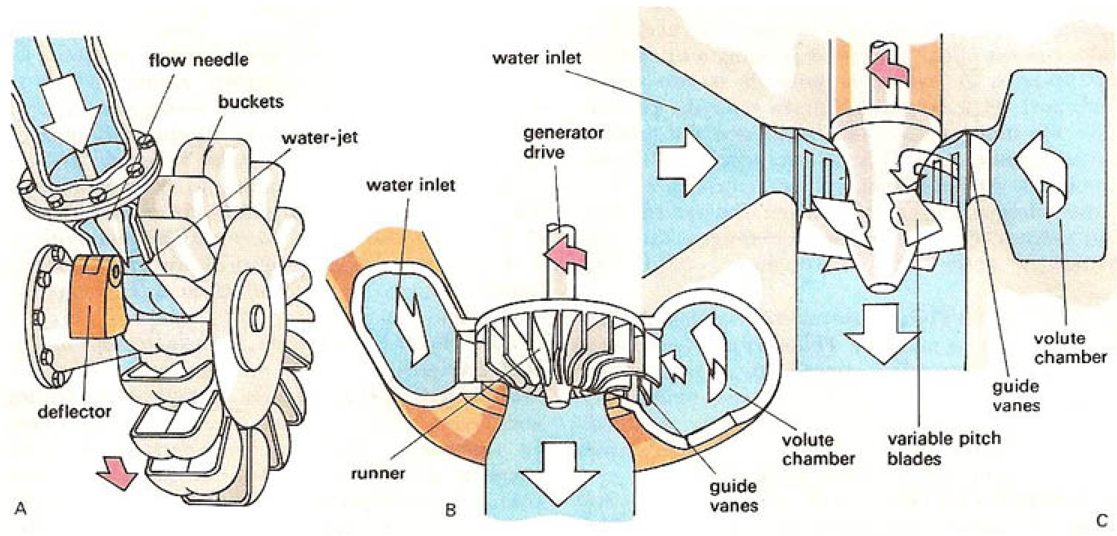
The available power closely depends on the available discharge (Q in m3/s) and the available head (H in m), the density of water ρ = 1,000 kg/m3, the gravity acceleration g = 9.81 m/s2 and ή the efficiency of the turbine (this can vary from 75 to 90%). The power in Watts (W) is computed with the following formula:

$$P = Q\ H\ \rho\ 9{,}81\ \eta$$

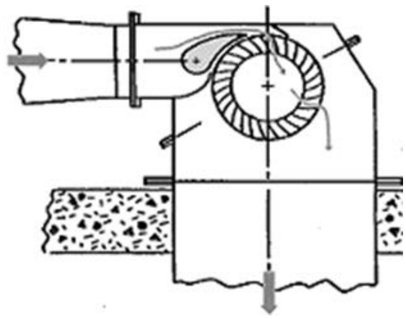
The theoretically power available from a flow of 1 m3/s water falling 1 m is therefore 9,81 W.

Due to energy loss the practically available power will be less than the theoretically power with the application of the efficiency coefficient η which value is comprised between 0.75 and 0.95.

The following picture illustrates the 3 main types of turbines.

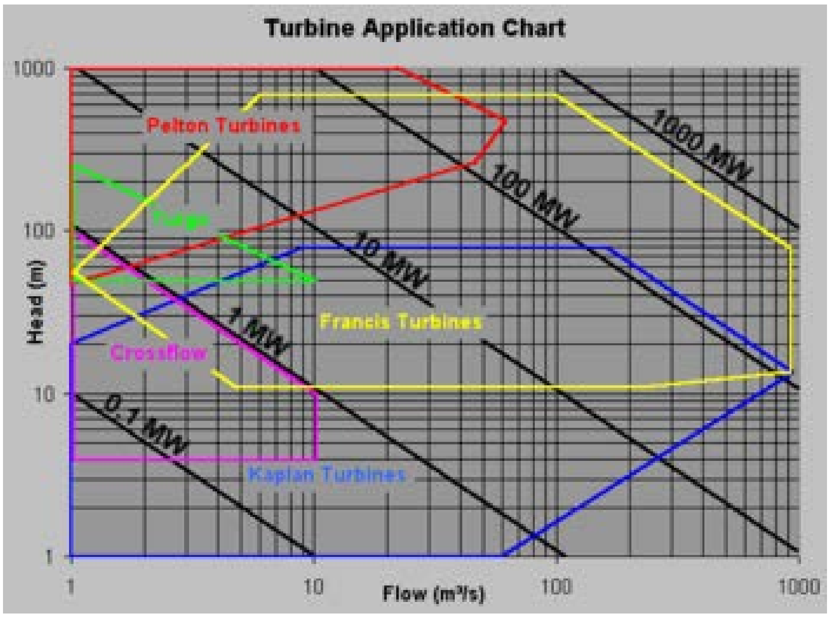


A Pelton **B Francis** **C Kaplan**



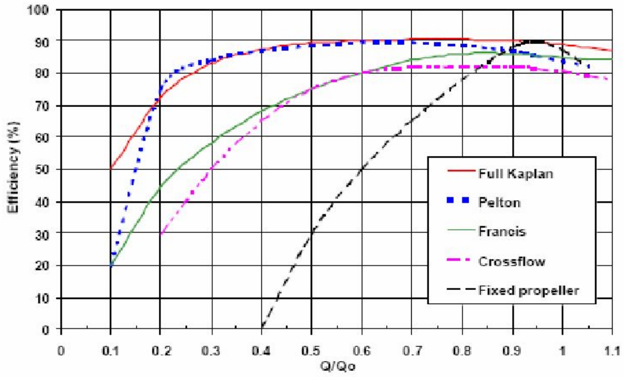
D Crossflow turbine also named Banki

The chart below illustrates their respective domains of utilization when combining the available head, the power output and the available flow discharge.



Small hydro turbines can attain efficiencies of about 90%. Care must be given to selecting the preferred turbine design for each application as some turbines only operate efficiently over a **limited flow range** (e.g. Kaplan turbines with fixed blades and Francis turbines). For most run-of-river hydro sites where flows vary considerably, turbines that operate efficiently over a wide flow range are usually preferred (e.g. Kaplan, Pelton, Turgo and crossflow designs). Alternatively, multiple turbines (such as Francis) that operate within limited flow ranges can be used.

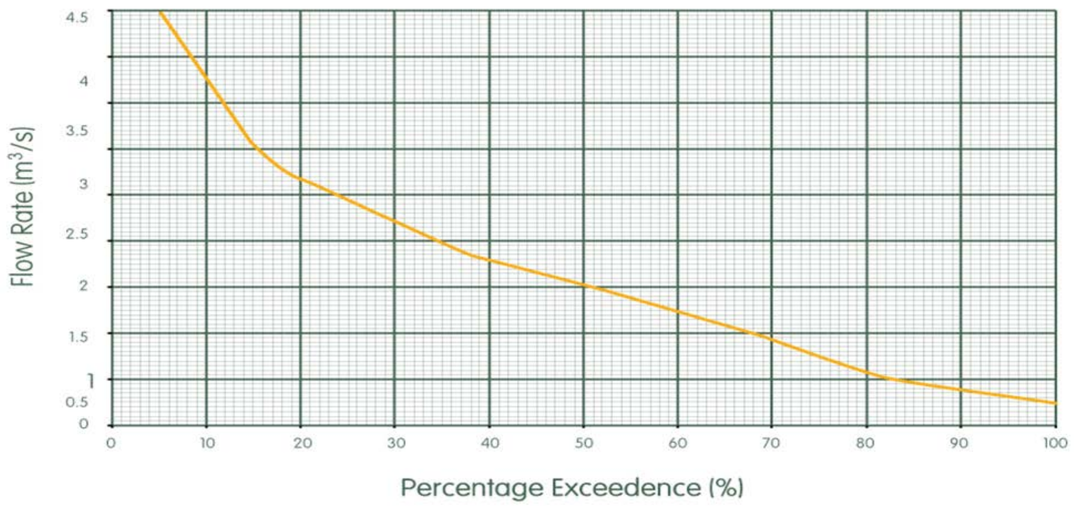
The following chart illustrates the efficiency curves for various types of turbines. It means that once selected, a turbine achieves its maximum of efficiency when it runs close to its main design parameters which are the available water head and the flow discharge.



Small hydro projects can generally be categorized as either "run-of-river developments" or "water storage" (reservoir) developments. **"Run-of-river"** refers to a mode of operation in which the hydro plant uses only the water that is available in the natural flow of the river. This implies that there is no water storage and that power fluctuates with the stream flow so they are often best suited to provide energy to a larger electricity system.

"Water storage" refers to a mode of operation in which water is stored in a reservoir. This allows to provide power on demand, either to meet a fluctuating load or to provide peak power. Unless a natural lake can be tapped, providing storage usually requires the construction of a dam or dams and the creation of new lakes. In some cases, this can seriously impact the local environment.

The **Flow Duration Curve** is the most fundamental piece of information needed for the design of a hydropower project. It is a plot that shows the percentage of time that the flow in a stream is likely to equal or exceed a specified value. In the graph below, as an example, during 50% of the time the discharge will equal or exceed 2 m3/s.



In general, the selection of turbines is done in order to cover the largest range of flow (exceedence varying from 20% to 80%)

In some installations the water flow rate can vary by a factor of 100:1 over the course of a year (and sometimes dry-up for a few weeks). For most mini hydro in sub-Saharan Africa, it can be estimated that the load factor may vary from 0.2 to 0.7. This means that an economic arbitrage needs to be done for the selection of turbine technology and number of turbines.

To enable to operate at an acceptable level of efficiency over a wider range of flow, 2 turbines in parallel and, some times, 3 turbines may be advised.

The determination of the type of turbines and of their optimal numbers is made in an energy maximisation and profitability of investment perspective. To that effect the specific efficiency characteristics of the various types of turbines are considered. In the same way the mode of operation of the plant is taken into account.

4 Typical benchmarks

Classification of hydro plants

It is generally accepted to classify hydroelectric plants according to their size. The most common classification of hydroelectric plants, based on their size, is as follows:

- Pico-hydro: less than 10 kW
- Micro-hydro: from 10 kW to 500 kW
- Mini-hydro: from 0.5 MW to 10 MW
- Small-hydro: from 10 MW up to 50 MW
- Large-hydro: from 50 MW up to 200 MW
- Very large-hydro: above 200 MW

Cost of energy produced

The indicator commonly used is the Levelized Cost of Energy (LCOE). It is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. The lowest LCOE is attributable to hydropower plants of medium to large size. In general, the larger the hydroelectric plant, the cheaper the cost per kilowatt-hour to produce the electricity. The following table provides a comparison with other sources of energy.

Plant Type	Levelized Cost of Energy US $/MWh		
	Max.	Median	Min.
Large Scale Hydropower	130	70	30
Small Hydropower	150	80	20
Wind Offshore	200	180	90
Wind Onshore	120	90	60
Solar PV	180	140	60
Solar CSP	240	160	150
Coal, integrated gasification combined cycle	160	80	40
Natural Gas Combined Cycle	160	110	60
Nuclear	160	110	90

Source: EU Technical Assistance Facility for the SE4ALL Initiative

5 Economic and environmental impacts

Costs and economic aspects

Hydropower schemes are infrastructures of capital intensive nature at the time of their construction. However their costs closely depend on the type and dimensions of the associated dam. The best part is that their operating and maintenance costs are very low.

The overall cost breakdown is as follows:

- Capital cost comprising:
  - Civil/structural material and installation, (in general 40-50% of the total cost)
  - Mechanical equipment supply and installation, (in general 10-20% of the total cost)
  - Electrical instrumentation and controls ("I&C") supply and installation, (5% of the total cost
  - Project indirect costs, fees and contingency, and (10-15% of the total cost)
  - Owner's costs (5-7% excluding project financing costs)
- Operation and Maintenance costs (O&M) including:
  - Fixed O&M costs (are those that do not vary significantly with generation)[1](
  - Variable O&M costs (are production-related costs which vary with electrical generation)
  - Major Maintenance costs[2]

The cost varies from US $ 2,000 to 5000 per kW installed for the construction of a hydropower plant. The unit cost is indeed highly dependent on the site conditions and on the complexity of the associated civil structures. It may be higher for water storage developments (the cost of the dam

[1] Operating labour cost is usually low, as plants are automated and have few personnel on site during normal operation

[2] Maintenance repair and replacement of large electro-mechanical equipment require skilled staff and import of very specific equipment and spare parts that are often not available on the African market

being important) or lower for run-of-river scheme with highly favorable hydraulic and topographic features.

The advantages of small hydropower plants are of various natures:

- low cost of electricity production:
  - Less than US $ 10 cts per kWh under favorable site conditions
  - A new hydroelectric power plant will displace the power generation of a less cost-effective fossil fuel power plant.
- in general limited negative impact on the environment:
  - True for the plants of the run-of-river type
  - Reduced CO_2 emission with "avoided" fossil fuels burning
- very well-known and reliable technology
- low intraday power production variability:
  - Full generation capacity can be available within a few seconds.
- low operating and maintenance cost
- long economic lives:
  - Life span is projected for at least 50 years.

The noticeable disadvantages are that hydropower plants:

- require large initial investments
- need complex studies and time consuming onsite investigations
- are subject to award of permits and authorizations to be delivered by authorities
- impact the river management and the downstream users and biotopes
- need several years of construction
- run-of-the-river power plant provides a "non-firm" power supply. During non-forecasted low generation period (e.g. exceptional drought), back-up (fuel based) systems are required to deliver substitute electricity to ensure continuity of supply.

Socio environmental impacts

Hydropower projects have direct impacts on the environment by disturbing or modifying the flow of rivers (at least on a portion of the river) and by inundating important areas in the case of storage reservoirs.

They also impact populations when they have to be expropriated, compensated, displaced and resettled.

The corresponding mitigation measures to reduce such impacts are nowadays well defined through good practices and guidelines established by multilateral development institutions, ONG's and through the participative engagement of the civil society and all stakeholders during the preparation and design of the project.

In addition to providing electricity for socio-economic development, some major positive effects of hydropower schemes are:

- Contribution to regulation of the river flow and reduction of (destructive) floods
- Better access to water resources for various purposes (water supply, irrigation)
- Creation of economic activities in the reservoir area (tourism, fisheries, navigation)

- Benefit sharing and compensation mechanisms towards local communities for the use of local resources

A contrario, impacts which require to be carefully considered are:

- Displacement of populations and inundation of land to be fairly compensated through adequate appraisals and consultative approaches
- Direct impact on the fauna and flora in the project area
- Disturbance of the river flow to be mitigated by a minimum environmental discharge to maintain downstream biotopes and take into account downstream riparian users interests
- Management of the catchment area in order to limit the erosion of soils and the siltation in the reservoir

In general, design, construction and operation of hydropower schemes must comply to good practices and environmental laws existing in the majority of countries worldwide, including Africa. When project financing includes the support by multilateral development institutions, Environmental and Social Impact Assessment (ESIA) studies are required to be conducted as per established guidelines, safeguards and operational policies of these organizations.

Rehabilitation of existing hydro power plant

The profitability of the rehabilitation of an existing hydro power plant in order to extend its technical life or to recover the lost capacity because of poor maintenance or obsolete technology or to use a higher share of the river's hydro capacity through capacity expansion may reach 15-17%. The main difficulty is the need to limit the decline or interruption of power plant generation that may provide a significant share of power in a country.

6 What are the major studies required?

Cost of studies and time frame

The implementation (up to commissioning of operations) of a hydropower scheme project depends of course on its dimension. There is a usual sequence of steps which can be broadly summarized as follows:

Step/Phase	Indicative duration range	Main Activities/Method
Identification	3 to 6 months	On site reconnaissance, Desk studies, data analysis
Pre-feasibility study	6 to 18 months	On site surveys, preliminary design and computations
Feasibility study (Including ESIA studies)	12 to 36 months	On site surveys, in situ tests, economic analysis, cost estimates, design development
Detailed design	10 to 18 months	Computations, modeling, bills of quantities
Tender documentation	3 to 9 months	Bidding documents, contracts models
Tendering/Bidding period (till award of contract)	Min 3 to 9 months	Contractual and administrative documentation package
Mobilization of financing	9 to 18 months	Commitments of lenders and financing agreements
Implementation	18 to 36 months	Construction, commissioning

The durations in the above table are indicative only. Broadly for a totally new project, the duration from identification to commissioning can span from 5 years to more than 12 years in the worst case when phases are not achieved in due time, thus depending also on the size and complexity of the project.

Studies and investigations

Hydropower plants projects require complex studies and investigations in various domains. Generally, the studies and surveys must comprise the following topics:

- Topography and geomorphology of the site
- Evaluation of the water resource and its generating potential
- Site selection and basic layout
- Hydraulic turbines and generators and their control
- Environmental impact assessment and mitigation measures
- Economic evaluation of the project and financing potential
- Institutional framework and administrative procedures to obtain the necessary consents

Further on, specific expertise is required and computations must be conducted in details in the following technical fields and engineering sciences:

Hydrological studies: collection from water resource administration, existing gauging stations and analysis of water flow data over a 20-30 year period[3]to establish Flow Duration Curve and select the project design flood.

The discharge flow of a run of the river hydro scheme must be corrected of the existing and future water abstractions (irrigation, city water) between the location of the gauge and the location of the weir. The watercourses are shared with several users such as the farmers, industry, fishermen. Relations with the water users and the administrations are sometimes difficult and this would require a dialogue to be established to progress appropriate actions.

The aim is to determine the capacity of the plant, the number of turbines, the spillway dimension and to outline the guidelines for the future operations of the plant. The surveys on the solid material transport in the river will determine the need for de-silting or sand-trap facilities and the evaluation of the evolution of the useful capacity of the reservoir during the life of the project.

A mini-hydro power plants must be designed to safeguard its physical integrity against adverse geophysical, weather and climate conditions, or to support degradations that can be repaired at affordable cost.

Mini-hydro power plants must be designed to be resilient to the worst high water flow known as **flood design** level criteria. High water may potentially destroy the intake weir and cause loss of life if it is not designed to resist to the high water pressure. It could also flood the powerhouse and switchyard which would be extremely damageable to the mechanical and electrical equipment.

Determination of the flood design levels for dams and associated hydropower structures is made from a determination of the flood hydrograph for various flood events and then from investigation of the way that the floods can be routed away or through the structure concerned.

According to good international standard practice the selection of the magnitude of the flood for design purposes is mostly based on the acceptable degree of safety, based, in turn, on engineering and economic considerations, but mostly on the risk to human life.

[3]The proven water resource is based on long term statistical series to account for climatologic cycles

Project design flood: The project design flood is a hypothetical "maximum probable" flood that may occur during the life of the project. The infrastructures must stand this flood without damages. Hydraulic structures and project components must be dimensioned in order to allow the flood to pass through and the levels of water maintained below a given elevation to avoid inundation. Flood frequency analysis uses historical records of peak flows to produce guidance about the expected behaviour of future flooding. Two primary applications of flood frequency analyses are:

1. To predict the possible flood magnitude over a certain time period
2. To estimate the frequency with which floods of a certain magnitude may occur

Then the **return period**, or recurrence interval of a flood of a given magnitude is estimated. As example, a 100–year flood is less frequent but larger in magnitude than a 25–year flood. The 25–year flood occurs on average once every 25 years and has an exceedance probability of 1 over 25, or 4 percent, in any given year. That's a 4 times greater chance than the 100–year flood, which only has a 1 percent exceedence probability in any given year. The 100–year flood is smaller in magnitude and 5 times more frequent than the rare 500–year flood, which has a 1 over 500, or 0.2 percent chance of occurring in any given year.

Geological investigations: The geological patterns under main civil works must be identified as well as faults and geological singularities which may impact the stability and the safety of the works. Seismological patterns of the area are also needed for works stability computations.

Geotechnical investigations: The soils properties at the location of the foundations of the main works must be determined as well as characteristics of construction materials at borrow areas. Investigations are performed through in situ surveys and identification, laboratory testing and drillings both during studies and further at the time of construction.

Geographic review: topographical survey, location plan with contour lines, plant layout with contour lines, review of infrastructure facilities. The analyse of topographical information together with the water available and resulting costs enable to work out the best optimal location for the civil structures and the best gross head obtainable.

Design of civil works: reservoir, diversion weir (design calculation for weir, spillway and dissipater) and intake structure (design calculation, plan and section) including intake trash rack with details of intake gate and single flushing gate, waterways (plan and cross section) and protection wall, forebay (design calculation, plan and section) including trash rack, penstock intake and spillway, penstock (plan and section), bulk head gate (details), power house (plan, section), tail race channel, hydraulic head and head loss calculation, approach roads.

Landslides that would result from heavy rain could displace or distort the penstock or fill with mud and gravel the open channel between the water intake and the forebay. The civil works will also be designed with the adequate coefficient corresponding to the seismic zoning risk.

Power study: head and flow rate, calculation of power generation capacity of the plant and placement of the generated power into the existing electrical transportation/distribution systems.

Design of mechanical equipment and specification data sheets: penstock (water hammer calculation and design of surge tank, selection of appropriate material, design of thickness), main inlet valve, hydraulic turbine, turbine control and governing system, oil pressure unit, cooling plant, dewatering and drainage system.

Design of electrical equipment and specification data sheet: generator, voltage regulation panel, electrical and safety control systems, switchyard, MV and LV lines to the local electric transportation/distribution network.

Operation tools: list of critical operational spare parts, list of tools. Operation manual and water management procedures.

Environmental and social impact assessment: surveys and enquiries for Baseline establishment. Dialogue with populations and future beneficiaries and consultation with all stakeholders at large. Identification of sensitive ecological features for designing mitigation and compensation measures.

Economic studies: costs estimates (bill of materials and costs data sheet), operating and maintenance costs, feed-in-tariff applicable and expected income, cost-benefit analysis. Economic computation for determining Economic Rate of Return, sensitivity analysis.

7 Key questions

Feasibility analysis
How far is the hydro site from the grid?
Is there any reliable statistics on water flows over the past 30 years?

Financial analysis
What is the expected cost of the kWh produced? Is it below 0.1 USD?
Are the financial indicators (pay-back period, IRR, cost per installed kW) acceptable?
What mix of financing is the most appropriate to the local context?
Is the power purchase agreement bankable?
Is the off taker creditworthy?

Economic analysis
What is the impact of the project on the economic and incomes generating activities?
What is the expected social impact on the beneficiary population (education, health,)?

Environmental and social impact
Will some local population be displaced? If affirmative, how this population will be compensated?
What are the social measures which will be put in place during the project implementation?

Organisations and business models
What type of organisations is the most appropriate to the local context?
Is there any opportunity to rehabilitate ageing or ill-maintained existing hydro power plants?
What activities are currently authorised to the private sector and private individuals and what needs to be reviewed in the energy law, regulation, to allow the setting-up of new business models?

Technology
How can adequate service quality be maintained so that systems are not damaged?
To whose standards/norms the hydropower systems will comply?

Price and Tariff
Capability and willingness to pay of the various stakeholders

Operation and maintenance
How and who will operate and maintain the systems?
What will be the load factor of the installation and the equipment flow?

Business plan
Is a business plan available and realistic (competitor analysis, marketing plan, sales planning, per-kW economics, cash flow planning)?

8 Useful references and links

International Energy Agency – IEA	http://www.iea.org
National Hydropower Association – NHA	http://www.hydro.org
International Hydropower Association - IHA	http://www.hydropower.org
International Commission on Large Dams	http://www.icold-cigb.org
The World Commission on Dams – WCD	http://www.internationalrivers.org
Guide on How to Develop a Small Hydropower Plant	http://electrical-engineering-portal.com

Guide d'utilisation et qualité de l'énergie – petite centrale hydraulique, Leonardo Energy
http://www.leonardo-energy.org/small-hydro-power

Renewable power generation cost in 2012, IRENA
http://costing.irena.org/media/2769/Overview_Renewable-Power-Generation-Costs-in-2012.pdf

The conversion of nature into hydroelectricity, Gilkes Power
http://www.renugen.co.uk/content/hydro_brochures/gilkes_pelton_turbine.pdf

Renewable energy technologies, cost analysis series, Hydropower, IRENA
http://costing.irena.org/media/2778/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf

RET Screen International, Small Hydro project analysis,
http://www.retscreen.net/download.php/ang/109/0/Textbook_HYDRO.pdf

Petite hydroélectricité, guide technique pour la réalisation de projet, ESHA
http://www.esha.be/fileadmin/esha_files/documents/publications/GUIDES/GUIDE_SHP/GUIDE_SHP_FR.pdf

The Hydropower Sustainability Assessment Protocol
http://www.hydrosustainability.org/Protocol/Documents.aspx#.VGuYH8mlvyo

MINI CENTRALE HYDROELECTRIQUE Manuel pratique www.energie-environnement-upmc.fr/userfiles/file/cours/.../tp_hydro.pd...

Centrale hydroélectrique : le guide pratiquehttp://centrale-hydroelectrique.comprendrechoisir.com/

Guide pour le montage de projets de petite hydroélectricité ... – Ademe
www.ademe.fr/sites/default/files/assets/.../47883_guide_petite_hydro.pdf

Institute for Energy Research IER http://instituteforenergyresearch.org/analysis/electric-generating-costs-a-primer/

Etude sur le développement de l'hydroélectricité de moyenne et petite puissance en Afrique Sub-Saharienne – RECP – AFD – Tractebel Engineering – Décembre 2014
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