The special challenge in W-Africa

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Comparison Low Head vs. High Head

Generic Projects

The basic layout of a hydro power plant is decided based primarily on **topography** and on the **designated demand**

**Example: Run-of-River with Diversion Channel**

<table>
<thead>
<tr>
<th>Head</th>
<th>Example 1:</th>
<th>Example 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{net}$</td>
<td>100 m</td>
<td>10 m</td>
</tr>
<tr>
<td>$Q_d$</td>
<td>2.6 m³/s</td>
<td>27 m³/s</td>
</tr>
<tr>
<td>$P_{el}$</td>
<td>2.0 MW</td>
<td>2.0 MW</td>
</tr>
</tbody>
</table>
**NB: plant gradient**

(unit: %)

The quotient of the difference in altitude between the water level at the intake and the water level at the turbine outlet divided by the total length of the water conveyance structures from intake to the end of the tailrace channel. Common indicator for the attractiveness of a project. Projects with > 6% are very favourable, < 2% indicates low attractiveness.

\[
\text{Plant Gradient} = \frac{H_{\text{int}} - H_{\text{out}}}{L_{\text{total}}} \times 100 [\%]
\]

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**Examples: Intake**

<table>
<thead>
<tr>
<th>2-3 m³/s</th>
<th>25-30 m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usually smaller rivers with less destructive floods</td>
<td>Usually large rivers with high flood levels</td>
</tr>
<tr>
<td>→ less complex design and construction</td>
<td>→ complex design and construction</td>
</tr>
<tr>
<td>Long term gauging data for smaller streams rarely available.</td>
<td>Long term gauging data available for many rivers, analyses can be related to similar basins.</td>
</tr>
<tr>
<td>→ Own gauging required, analysis to be based on empiric approaches.</td>
<td>→ Frequently faster and more reliable analysis possible</td>
</tr>
</tbody>
</table>

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**Example: Channel**

<table>
<thead>
<tr>
<th>2-3 m³/s</th>
<th>25-30 m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively small cross section, but long channel</td>
<td>Relatively large cross section, but short length</td>
</tr>
</tbody>
</table>

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**Penstock: Economic diameter**

Computation of the most economic penstock diameter usually is a time consuming task. Additionally, many of the required economic and technical parameters may not yet been known at a certain stage of project development.

→ use rule of thumb (empiric formula):

\[
D_{\text{opt}} = \frac{1}{2} H \left( \frac{P_{\text{hydr}}} {H} \right)^{\frac{3}{5}}
\]

where

- \(D_{\text{opt}}\) = optimum diameter (in m)
- \(H\) = gross head of the hydro power plant (m)
- \(P_{\text{hydr}}\) = hydraulic power = \(\rho \times g \times Q \times H\) (kW)
Examples: Penstock Optimum Diameter

<table>
<thead>
<tr>
<th>2.6 m³/s</th>
<th>27.0 m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usually long pipe, but small diameter.</td>
<td>Usually short pipe, but very large diameter.</td>
</tr>
<tr>
<td>( D_{\text{opt}} \sim 1.0 \text{ m} )</td>
<td>( D_{\text{opt}} \sim 4.0 \text{ m} )</td>
</tr>
<tr>
<td>( v \sim 3.3 \text{ m/s} )</td>
<td>( v \sim 2.2 \text{ m/s} )</td>
</tr>
<tr>
<td>L \sim 350 \text{ m}</td>
<td>L \sim 40 \text{ m}</td>
</tr>
<tr>
<td>total weight \sim 9 \text{ tons}</td>
<td>total weight \sim 3 \text{ tons}</td>
</tr>
</tbody>
</table>

Turbines

- **Low Head**
  - AXIAL
- **High Head**
  - FRANCIS
  - PELTON

Examples: Powerhouse and Turbine

- **Madland HPP, Norway**
  - 1 Francis, \( D_r = 572 \text{ mm} \)
  - \( P = 1.9 \text{ MW}, H = 84 \text{ m} \)
  - Photo: Gugler

- **Gstatterboden HPP, Austria**
  - 1 Axial Bulb, \( D_1 = 1\,950 \text{ mm} \)
  - \( P = 2.0 \text{ MW}, H = 9.4 \text{ m} \)
  - Photo: Andritz Hydro

Specific Types of HPP

- Hydropower Barrage
- Hydropower Dam
Run-of-River (ROR) and Reservoir (RES) HPPs have different electricity supply characteristics

Run-of-River (ROR) HPP
- These schemes usually supply base load.
- Seasonal variations in generation may occur (i.e. below design capacity operation in dry season).
- Flow available for power generation limited to the actual river flow, no storage capacity.

Reservoir (RES) HPP
- These schemes can supply peak load.
- River flow, as energy source, can be stored and released through the turbine during times of high demand (e.g. ‘evening peak’).
- Very large reservoirs may provide seasonal storage capability.

River Barrage
- Low head and large flow usually result in large structures and turbines, and correspondingly in high costs per installed capacity.
- In large hydro these schemes are often built as cascades, frequently with a large ‘head reservoir’ upstream.
- May have substantial environmental and social impact if large upstream areas are converted to reservoir.
- As it usually blocks off large rivers which are required for navigation. Adequate measures have to be implemented (expensive in implementation and operation!)
- In some countries (if environmental legislation permits) these schemes are operated to provide balancing load, resulting in fluctuating water levels.

Hydropower Dams
- Common only above 10 MW (large hydro)
- Usually medium to high head
- Frequently hydropower dams have substantial strategic value for a utility as they provide peak / balancing capacity.
- Seasonal storages allow increased hydropower generation during dry seasons and impact on the operation of downstream hydropower plants.
- Multi-purpose projects: Dam might serve for various purposes with different priorities (drinking water, irrigation, river control, etc.)
- Such projects are generally expensive!
- Power market does not provide adequate tariffs in most countries for IPPs.

Comparison On-Grid vs. Off-Grid
Optimisation criteria for on-grid and off-grid HPPs are very different

**On-grid**
- Aim is to maximise the economic attractiveness of the project
- Adjustment of the capacity to maximise the rate of return on the investment
(NB: Limited validity non-commercial projects)

**Off-grid**
- Aim is to ensure provision of peak demand throughout the year.
- Provision of the ‘least cost option’ for electricity supply

Summary and comparison of different types of HPP plants

There are 3 main types of MHP commonly found

<table>
<thead>
<tr>
<th>Grid Connected</th>
<th>Captive</th>
<th>Stand Alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-grid</td>
<td>commercial projects</td>
<td>usually rural electrification</td>
</tr>
<tr>
<td>usually commercial projects</td>
<td>Private sector</td>
<td>Usually not viable on a fully commercial basis</td>
</tr>
<tr>
<td>Private sector</td>
<td>Always implemented on a fully commercial basis</td>
<td></td>
</tr>
<tr>
<td>Mostly implemented on a fully commercial basis (government-run utilities might follow other objectives as well)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium / High level technology adopted</td>
<td>Mostly viable from relatively small size ranges</td>
<td></td>
</tr>
<tr>
<td>Only viable from a certain size (economy of scale)</td>
<td>Operated &amp; Managed by the industry owning the scheme</td>
<td></td>
</tr>
<tr>
<td>Operated &amp; Managed by professionals staff</td>
<td>Often combined with electrification for staff</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of Supply</th>
<th>peak generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-grid</td>
<td>normally grant financed</td>
</tr>
<tr>
<td>off-grid captive</td>
<td>Usually not viable on a fully commercial basis</td>
</tr>
<tr>
<td>off-grid standalone</td>
<td>Low to medium level technology adopted</td>
</tr>
<tr>
<td>off-grid islanded</td>
<td>Small size ranges</td>
</tr>
<tr>
<td>off-grid islanded</td>
<td>Usually official procedures relatively uncomplicated</td>
</tr>
<tr>
<td>off-grid islanded</td>
<td>Usually managed by community</td>
</tr>
</tbody>
</table>

Note: (1) primary purpose of dams / reservoirs: flood control (2) Not primary purpose of this HPP Type (secondary energy, climate change)
Most potential issues and challenges are primarily attributed to commercial schemes

Mainly related to grid connected commercial schemes but also applicable to some extent to off grid and captive schemes

<table>
<thead>
<tr>
<th>Item</th>
<th>on-grid</th>
<th>captive</th>
<th>isolated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory and Promotional Issues</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Project Identification and Definition</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Project Risks</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Power Purchase Agreement</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Financing Constraints</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Project Implementation Structuring</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Example on-grid vs. off-grid: indicative design flow for a run-of-river HPP

- The on-grid HPP ( ) uses a much larger design flow than the off-grid HPP ( ).
- The installed capacity (directly related to the flow), would be much bigger for the on-grid scheme.
- The on-grid scheme can run on full capacity only during 30% of the time, the off-grid HPP can generate the full capacity during 95% of the time.

Thank you for your attention!

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The Francis Turbine

Medium head ROR with moderate flow fluctuation

• The Francis turbine is the oldest and probably the best-known reaction turbine.
• The runner consists of a row of curved blades which form channels through which the water is accelerated and redirected.
• Regulation of flow is accomplished by a row of adjustable blades, the so-called wicket-gates or guide vanes, which are arranged concentrically around the runner.
• For very low head applications (<10 m), Francis turbines come in the form of open flume or pit-type machines. For higher heads up to 200 m, spiral casings are used.
The Pelton Turbine
High head schemes with relatively small discharges

- Turbine consists of a runner with a number of buckets on which one or more water jets impinge.
- Flow and hence power output is typically adjusted by a spear valve which can increase or decrease the nozzle opening.
- For higher flows the number of jets can be increased.
- Highly efficient turbine also for part-flow operation down to 10% of design flow.
- By installing a jet deflector the pressure surge in the penstock can be avoided.

The Crossflow Turbine
'Robust working horse' in MHP for low to medium head

- Cross-flow turbines are very robust and relatively simple machines and are therefore highly recommended for small scale rural electrification where operators might be limited in availability of skills and maintenance support.
- The efficiency of cross-flow turbines (up to 80%) is lower compared to other turbine types.

Propeller-Type Turbines

- Propeller turbines are reaction turbines. Flow passes through the runner in axial direction with little to no inward deflection.
- The oldest propeller type turbine is the Kaplan turbine (see next slide) with a scroll or spiral casing and radial wicket gate configuration for flow regulation similar to the Francis.
- Propeller turbines are also available in the form of tube, bulb and S-turbines.
- Propeller turbines with non-adjustable runner blades (different from the Kaplan-principle) have a less good part-flow efficiency.

The Kaplan Turbine
Low Head Run-of-River Plants with High Discharge

- The classic Kaplan turbine has both adjustable blades and adjustable wicket gates which gives best efficiencies over a wide range of flow rates.
- The axial-flow Kaplan turbine was invented by Viktor Kaplan in 1912.
- This type of turbine is perfectly suited for HPPs with high discharges and relatively low heads (run-of-river).
Example: SHP Kaplan Turbine

Example: S-Type Propeller Turbine

Part-Flow Efficiencies for Different Turbines

Examples: Intake

- 2-3 m³/s
- 25-30 m³/s