HYDROPOWER EUROPE

POWERING EUROPE IN A SUSTAINABLE WAY

Hydropower Technologies

The State-of-the-Art

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DISCLAIMER

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Acronyms

Acronym	Description
AAR	Alkali-Aggregate Reaction
ASR	Alkali-silica reactions
CFRD	Concrete face Rockfill Dam
CFSM	Converter fed synchronous machine
CMS	Condition Monitoring System
CPS	Cyber-physical systems
DEF	Delayed Ettringite Formation
DFIMs	Doubly fed induction machines
DM	Data mining
GHG	Greenhouse gas
GRP	Glass reinforced plastic
HDPE	High Density Polyethylene
HVdc	High-voltage direct current
IoS	Internet of Services
IoT	Internet of Things
ISA	Internal Sulphate Attack
LCOE	Levelised cost of energy
M	Magnitude of earthquake
MW	Megawatt
OBE	Operating Basis Eathquake
PC	Personal computer
PLC	Powerline Communication
RTU	Remote Terminal Unit
RCC	Rolled Compacted Dam
R&D	Research and Developpement
RoR	Run-of-river
PSH	Pumped Storage Hydropower
PSP	Pumped Storage Plant
PVC	Polyvinylchloride
SEE	Safety Evaluation Earthquake
SCADA	Supervisory Control and Data Acquisition
TRL	Technical readiness level
UAV	Unmanned aerial vehicle
USACE	United States Army Corps of Engineers
VSC	Voltage source converter

1 Introduction

Since the late 19th century, hydropower has developed as a clean, safe, reliable and inexpensive source of power and energy service. Hydropower generation corresponds to about 12% of the European net electricity generation and 36% of electricity from renewable resources in Europe (EUROSTAT, 2019). Hydropower is technically mature and is usually economically competitive under liberalized market conditions. It also provides significant benefits to the whole power system; in fact, the fast response capabilities provided by reservoirs and pumped storage plants provide critical energy to electricity networks, helping to match fluctuations in electricity demand and supply from intermittent and less flexible electricity sources. Moreover, since hydropower is situated at the crossroads of two major issues for development, water and energy, hydro reservoirs can often deliver services beyond electricity supply. Hydro storage capacity can mitigate freshwater scarcity by providing security during low flows and drought for drinking water supply, irrigation, flood control and navigation services. Multipurpose hydropower projects may have an enabling role beyond the electricity sector to secure freshwater availability.

Hydropower is a controllable (or dispatchable) renewable energy source. This is in part due to control over the source through its storage capabilities, and the greater predictability of its generation in comparison to wind and solar power. Hydropower is, however, variable over longer time scales, as it depends on precipitation and water run-off. At a regional level, climate change may affect the potential for power generation (even if there is no clear pattern across Europe), but at the same time its role in water management using reservoirs can contribute to mitigating negative effects in term of water availability.

Overall, hydropower has great potential to enable the transition towards a decarbonised economy in Europe (as it plays an important role in balancing the grid and mitigating the negative effects of intermittent generation from variable RES) and to mitigate the negative effects of climate change (by storing and supplying water). However, long legal proceedings, public opposition and unfavourable market conditions (e.g. low electricity prices, missing spreads). Environmental issues related to the impact on the flow regime upstream and downstream of dams and reservoirs, barriers to fish migration, loss of biodiversity and the alteration of river morphology are also a matter of concern. The hydropower industry has been making significant efforts to mitigate the negative effect on the environment of hydropower plant and considerable improvements have been implemented in recent years. Although significant progress has been made in addressing these issues, there is still a low level of awareness among the general public regarding these achievements.

Over the past decades, hydropower equipment has been optimized to achieve high performance, availability and flexibility. Regarding hydropower infrastructure, innovative measures to mitigate environmental impacts have been developed. Moreover, significant improvements have been enabled by computer technologies in many areas, including design, construction, monitoring, diagnostics, protection and control. Investment into research and development (R&D) is fundamental to meet advances in technology and to deal with market competition. Furthermore, to manage environmental and socioeconomic aspects at a regional level, there is a need to build links between industry, R&D and policy institutions.

The scope of this document is to provide an overview of the state-of-the-art of hydropower technologies and techniques, in order to set a baseline reference to identify and prioritise future R&D actions. It first introduces the main components of hydropower plants, reservoirs and the related infrastructure. It then looks at recent technological innovations enabling enhanced flexibility in power generation and storage, higher efficiency of hydropower plants, improved resilience of electromechanical equipment and infrastructure and better operations and maintenance. Finally, there is a discussion of current techniques and technologies to mitigate the environmental impact of hydropower projects.

2 Types of hydropower plant

2.1 Main components of a hydropower plant

Hydropower is based on a very simple physical concept. Hydropower plants convert the potential or gravitational energy of water first into mechanical and then into electrical energy: the flow of water turns a turbine, which is connected to a generator. The electricity generated then flows to a substation, where the voltage is increased, and is then distributed to the end user or fed into the power grid. Hydropower is a renewable energy as it is based on the water cycle, which is an endless, constantly recharging system.

Hydropower is a site-specific technology and needs to be tailored to the specific features of the local hydrology, topography and geology. However, while the design changes according to local conditions, the main components highlighted in Figure 2-1 are the **basic elements of conventional hydropower plants**. **Gates** are barriers that allow to regulate water release. They can take different forms, such as fixed wheel gates, sliding gates, radial gates, and caterpillar gates, and they are used for power intakes, bottom outlets, or river diversion works. Spillway gates are also used to control flood discharge in reservoirs.

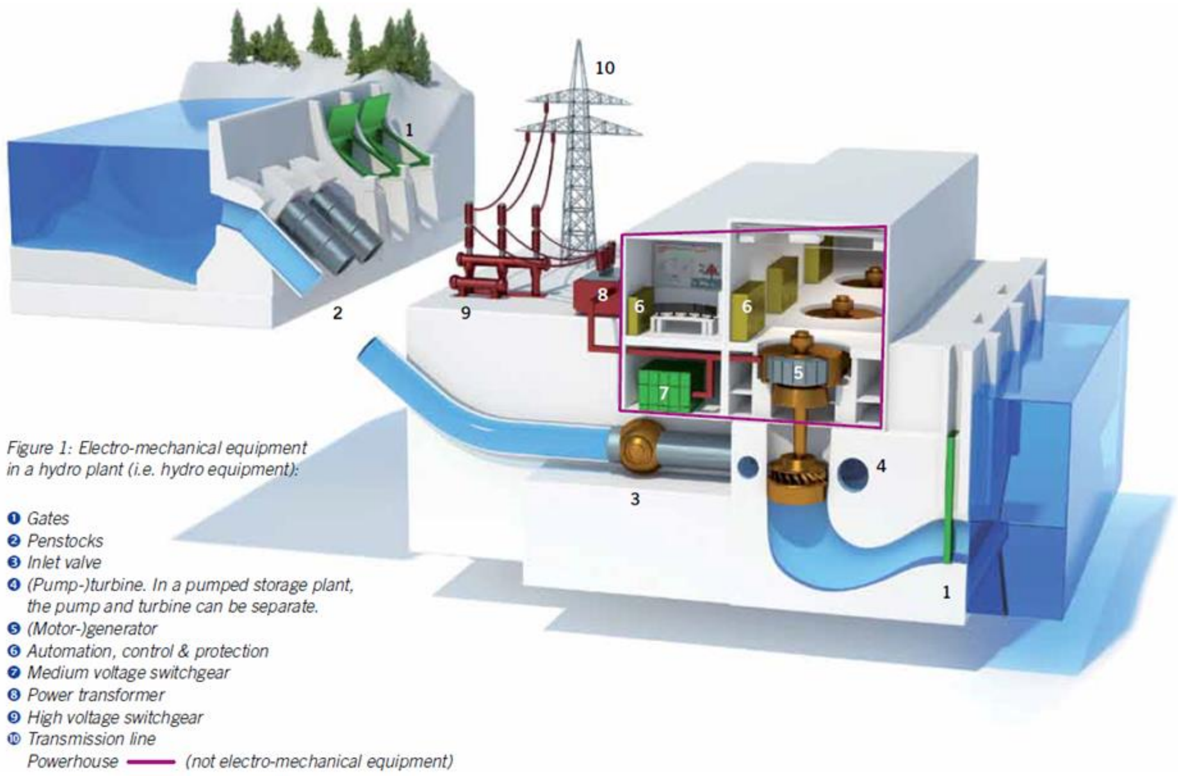


Figure 2-1 Electro-mechanical equipment in a hydro plant

When gates on the dam open, water flows down the penstock to the turbine, usually through a shut-off valve. The **penstock** is a conduit or pipe that conducts water from the intake to the powerhouse. Penstocks are usually made of steel and they must be able to withstand high pressures on the inside surface in the event of a sudden increase or decrease in the load - the so-called water hammer.

If the **powerhouse** is located far from the dam and reservoir, water is transferred by open channels, tunnels under pressure, or pressure shafts, which depending upon the rock type can be unlined, lined with concrete or steel lined. Sufficient water head should be available above the intake entrance to avoid the formation of vortices which may carry air into the penstock and result in problems with turbine operation.

A **surge tank** is often introduced in the system between the water intake and the powerhouse to absorb any water surges caused in the penstock or pressure tunnel due to the sudden loading and unloading of the generator through opening and closing of the inlet valve and wicket gates. The wicket gates of the turbine allow regulation of the amount of water that flows into the turbine.

The **turbine** is the machine that converts the kinetic/potential energy of water into mechanical energy. It is attached by way of a shaft to the **generator**, which transforms the mechanical energy of the turbine into electric energy. The turbine and the generator are at the heart of the hydroelectric power plant. Electricity is generated by the rotating magnetic field created by the spinning rotor, a series of large electromagnets, inside a tightly wound coil of copper wire, called the stator. The alternating current thus produced is transferred to the **transformer**, which converts it to a higher voltage. Finally, the high voltage electricity is transmitted to the **power line**. The water that passed the turbine flows through the draft tube into the tailrace channel and re-enters the river downstream.

2.2 Classification of hydropower plants

The amount of energy that a hydropower plant can generate is proportional to the product of the hydraulic head and the flow rate. The **Hydraulic head** is the difference in water levels between the intake and the discharge point of the installation. **Water flow** (or discharge) is the volume of water, expressed as cubic meters per second, passing a point in a given amount of time. The greater the hydraulic head and rate of water flow, the greater the potential energy that can be converted to electricity. Hydropower plants with low flows require high head, while plants with low head require high flows to generate the same amount of electrical energy. Due to the higher water pressure, higher heads also allow a higher flow rate through a smaller turbine thus reducing the cost of the equipment. Different types of turbine have been developed, such as Pelton, Francis and Kaplan to mention the most commonly used, in order to have the highest efficiency in power generation for different ranges of head and flow.

Hydropower plants are often classified in terms of operation and type of flow. According to this classification we can distinguish two main types of hydropower plant:

- **Installations equipped with a reservoir, which can be further divided into:**
    - Storage power plants;
    - pumped-storage power plants;
- **run-of-river power plants, which have a short residence time.**

Additionally, it is also important to consider:

- **offshore and tidal power plants** based on in-stream technologies;
- **hybrid power plants.**

Hydropower plants can also be classified according to their **size**, which varies consistently and spans from a few kilowatts to several gigawatts. This classification has led to the distinction between 'mini hydro', 'small hydro' and 'large hydro'. Nevertheless, there is no universally accepted definition of these categories: in fact, different countries have different legal definitions of size category that match their local energy and resource management needs. In most of the countries in Europe 'mini hydro' is considered below 1 MW, 'small hydro' below 10 MW and 'large hydro' above 10 MW. In any case, it is important to highlight that the great variety in the size of power plants allows hydropower to meet both large centralized urban energy needs as well as decentralized rural needs. Although the main role of hydropower is to provide electricity to a centralized energy system, it also often operates in isolation (off-grid) in rural and remote areas to meet local energy demand.

2.3 Storage power plant

Storage power plants are based on **impounding water** behind a dam. To produce electricity, water is released from the reservoir and sent to the turbine. The generating stations can be located directly at the dam toe without diversion of water or further downstream with diversion of water from the river; in this case the stations are connected to the reservoir through channels, tunnels or penstocks. Storage plants have the advantage that they are less dependent on the natural flow of water; in fact, according to their storage capacity, they can operate independently of the hydrological inflow by storing water during the wet season and using it during the dry season and even inter-annual. In other words, they can easily store potential energy to be converted into electrical energy when needed in a flexible way. For this reason, these plants are commonly used for intense load following and to meet peak demand, allowing the optimization of base-load power generation from other less flexible electricity sources. The larger the reservoir of a hydropower plant, the more storage it can provide.

In mountain areas, high-altitude lakes can be used as a reservoir preserving the characteristics of the original lakes. In this case, the power plant is linked to the lake through pressure tunnels and shafts by an underwater piercing of the lake. The hydraulic head may reach up to two thousand meters. In other areas, an artificial lake is usually created by inundating (river) valleys. A power plant can have tunnels connected to several reservoirs and can also be linked to neighbouring river basins.

Hydropower plants with large reservoirs offer the best level of services. Such plants can store energy on a large-scale during periods of low demand and make it available in periods of peak demand on an hourly, weekly, monthly or even seasonal basis. Moreover, their fast response time enables them to meet sudden fluctuations in demand. Hydropower plants with a small reservoir are mainly designed to modulate generation on a daily or maximum weekly basis.

Figure 2-2 Overview of a storage hydropower plant (*VSE-INFEL*)*with main elements starting from reservoir fed eventually by diversion tunnels from neighbouring catchment, arch dam, power intake, pressure tunnel, surge tank, pressure shaft, underground powerhouse, tailrace channel and switchyard.*

2.4 Run-of-river (RoR) power plant

Run-of-river hydropower plants use the natural flow of river water and do not involve any substantial storage. Therefore, these plants are less flexible than (pumped-)storage hydropower plants; in fact, run-of-river power plants operate under the constraint of precisely controlling the water level at the intake in accordance with the incoming river flow. The electricity output of run-of-river power plants depends upon the availability of water in the river and, therefore, can vary considerably throughout the year. Run-of-river hydropower plants typically provide baseload power, since the hydrological forecast is

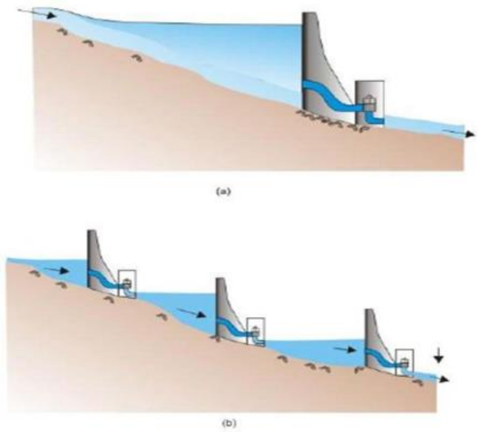


Figure 2-3 *a) single stage hydropower development scheme; b) cascade or multistage hydropower system* sufficiently good for the timescales required in the electricity market.

However, run-of-river plants may have some short-term storage possibilities (a few minutes dynamic cycle) and this allows for some adaptation to demand, especially for ancillary services such as frequency and voltage control. The design of run-of-river power plants varies significantly and can be optimized both for large flow rate with small head on a large river and small flow rate with a high head in mountain areas. In some cases, a portion of the river water might be diverted to a channel, tunnel or penstock to convey the water to a hydraulic turbine, which is connected to an electricity generator. Run-of-river plants can also be combined in a cascading or multistage scheme; in this case, two or more plants are located on the same river in sequence. Cascading schemes can produce during a few hours, peak energy by a simultaneous increase of production in all powerhouses. A storage power plant is often located in the upper catchment as it allows regulation of water flow to achieve constant energy output from the downstream run-of-river plants and to produce a few hours of peak energy in the whole cascade. Since the regulated river typically flows more evenly throughout the year, the combined cascade of dams and reservoirs allows optimisation of electricity generation and may also be used to absorb excess energy when reducing river flow.

2.5 Pumped-storage power plant

Pumped-storage hydropower plants operate with two reservoirs - a lower and an upper one. The two reservoirs are connected to each other through tunnels or penstocks. A pumped-storage plant moves water between the two reservoirs. In production mode, the plant operates like a conventional hydroelectric plant: water is released from the upper reservoir through the turbines to generate electricity. In pumping mode, electrical energy from the grid is used to pump the water from the lower reservoir to the upper one (usually during off-peak periods using surplus electricity generated by base-load power plants). In this case, a motor–generator is used to work either as a generator in the production mode or as a motor in the pumping mode. With regards to the hydraulic system the choice is between reversible pump-turbines able to work in both directions (usually these turbines are of the Francis type) or separate pump and turbine, such as in ternary systems. Reversible pump-turbines are more common for heads lower than 600 to 700 m. In this configuration, the direction of rotation must be reversed when the pumping mode is switched to the production mode and vice versa. A ternary system brings additional flexibility, since the pump and the turbine are separated on the same shaft and no change of direction is necessary.

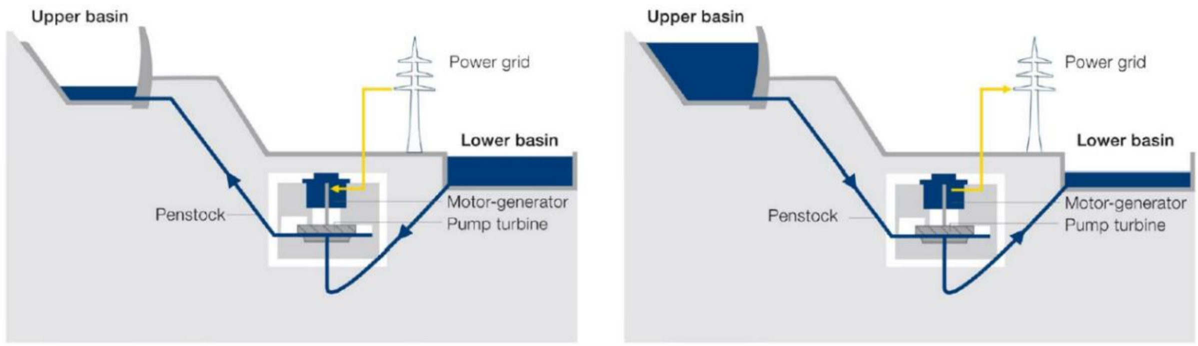


Figure 2-4 Functioning of PSH in pumping and turbining mode (Source: Voith)

Pumped storage power plants are operated depending upon the production of variable RES on daily and weekly cycles (the duration time for operation at full capacity is determined by the storage capacity of the upper reservoir) and are designed to provide peak electricity during periods of high electricity demand. Pumped-storage hydropower facilities are currently the most efficient and large-scale energy storage systems, with typical overall efficiency (cycle efficiency) in the range of 70–85%.

Depending upon the site topography and hydrological conditions, existing reservoirs or lakes may be used; if no reservoirs are available new ones need to be created. In some cases, the lower reservoir is a river controlled by a weir or a run-of-river power plant. Other concepts foresee the use of underground reservoirs. The use of abandoned mines, caverns, and man-made storage reservoirs has been investigated. Another option is the use of the sea as the lower or upper reservoir, but for the moment there is just one example of seawater pumped storage. Finally, small scale pumped-storage hydropower plants can be built within infrastructures, such as drinking water networks, navigation locks and artificial snow making infrastructures. This kind of plant are usually quite small in size and they provide distributed energy storage and distributed flexible electricity production.

Pumped-storage hydropower plants are net energy consumers; the ratio of produced energy to consumed energy for pumping the water ranges between 70% and 85%. However, this drawback is compensated for by the flexibility provided by these plants. Indeed, pumped hydropower is currently the more mature, flexible and cost-efficient form of bulk energy storage. Therefore, the role of pumped storage hydropower plants is twofold: balancing the grid for demand-driven fluctuations and balancing generation-driven fluctuations. Like conventional reservoir-type hydropower plants, pumped storage power plants can provide the full range of grid-stabilizing services.

2.6 In-stream technologies and offshore hydropower

Finally, it is important to stress that hydropower generation does not necessarily imply considerable civil works. In-stream technology refers to the use of hydrokinetic turbines to harvest the energy of naturally flowing water, such as stream, tidal, or open ocean flows, without impounding the water. This technology can be integrated into existing facilities like weirs, barrages, canals or falls to generate electricity. These facilities basically function like a run-of-river scheme.

A significant development potential exists for in-stream technologies through offshore hydropower, which is a less established but growing group of technologies that use tidal currents or the power of waves to generate electricity from seawater. More details on this and tidal hydropower plants are discussed in chapter 12.

2.7 Hybrid hydropower

In addition to the four types of hydropower plant mentioned above, it is worth mentioning the concept of hybrid power plants. Hybrid power plants work with one or more different types of generation as an integrated unit and can occupy a single site or comprise a microgrid. Hybrid power plants may be connected to the grid or be far from the grid in remote areas, where they represent the main source of power. In hybrid power plants, hydropower can be combined with solar or wind power to increase the stability and reliability of electricity generation. The hybridization allows PV panels or wind turbines to produce energy when the sun or wind is available, while saving water for hydroelectricity to complement during intermittent times when the sun or wind go down.

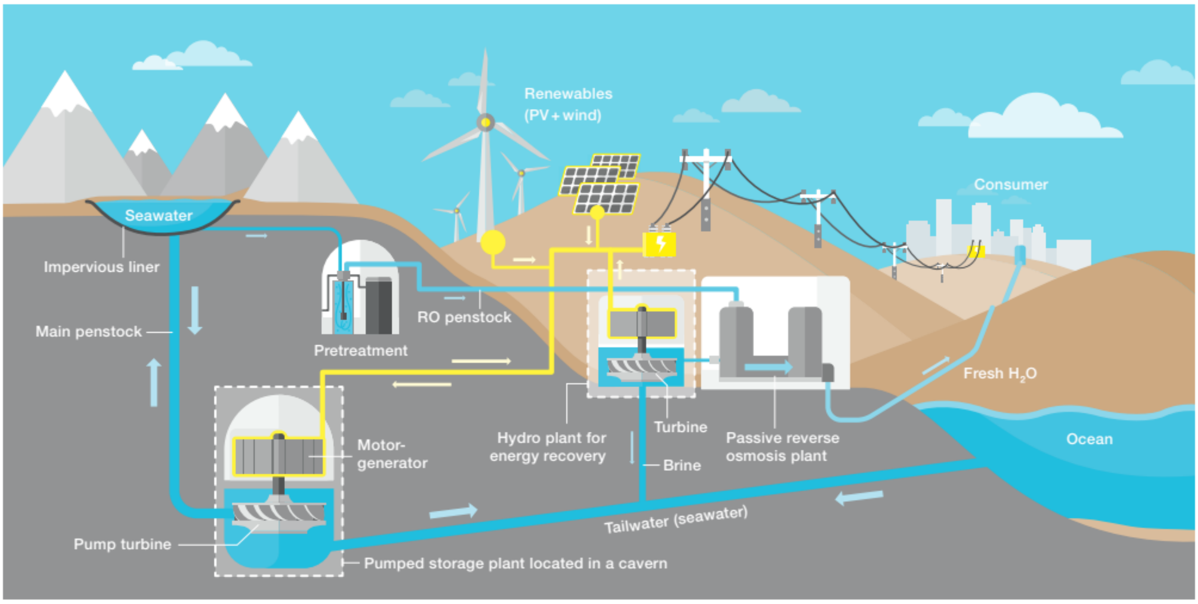


Figure 2-5 Example of a hybrid power plant combining seawater pumped storage, wind and/or solar power generation with a desalination plant (Source: Voith)

When pumped storage is possible, it also allows storage of excess energy to cover peak demand. Another advantage of hybridisation is the possibility to use the same electrical infrastructure for both generators, thus lowering overall capex costs. Additional benefits may also be gained by the combination of hydropower with floating photovoltaic, as the installation of solar panels on dead water spaces maximises the use of resources (although attention should be paid to the environmental impact of the floating structure and its anchors). Moreover, by covering a significant surface area on a body of water, these systems can reduce evaporation and algal bloom.

The examples above describe some of many possible configurations for hybridisation, while other options are subject to further development. These are always tailored to the site-specific demand for energy and/or water services.

3 Type of hydropower projects

Hydropower plants require high upfront investments but have a lifetime typically longer than one hundred years. However, electromechanical equipment often has a shorter lifespan, but nevertheless still very long (40 years or more). Moreover, about 60 % of the economically viable hydropower potential in Europe has already been exploited. An increase in electricity generation from hydropower can be achieved not only by building new power plants (greenfield projects), but also by refurbishing, retrofitting and upgrading existing infrastructures.

The main type of hydropower projects are:

- **Greenfield pure hydropower projects;**
- **Renovation, modernisation and upgrading projects;**
- **Multipurpose schemes.**

3.1 Greenfield pure hydropower projects

Greenfield pure hydropower project development entails identifying a suitable location and designing a hydropower plant that can optimise electricity production according to the specific topographical characteristics of the site. It is essential to properly investigate the long-term history and variability of water resources in the area through hydrological modelling based on the best historical data combined with global warming projections. Climate effects do not necessarily imply reduced water availability. In some cases, the hydropower scheme may need to be able to accommodate and optimize the use of increased rainfall or inflow. Then, specialized investigation of the site geology, including seismic risk, material availability and sediment transport are crucial and can greatly impact cost, financing and scheme viability. However, engineering issues are only one part of the equation. It is also critical to consider the project stakeholders, the local communities and environmental issues from the earliest thoughts and discussions about a new hydropower development. This implies giving due consideration to social and environmental impacts throughout the project lifecycle (including those around changes in land use and ownership) and consulting and engaging with affected communities so that they receive a net benefit from the project.

3.2 Renovation, modernisation and upgrading projects

Renovation, modernisation and upgrading of old power plants is less costly, requires less time and usually has a smaller or even no additional environmental and social impact than developing a new power plant. These types of project usually consist of selectively replacing or repairing components in the powerhouse (such as runners, generator windings, governors or control panels). Normally, electromechanical equipment needs to be replaced after 30-40 years, whilst the civil structures last longer before requiring renovation. The overall lifespan of a hydropower plant exceeds 100 years when properly maintained. Upgrading projects may lead to incremental increases in hydropower generation due to the use of more efficient turbines and generators. Moreover, retrofitting the power plant using generating equipment with improved performance often provides a solution to market demands for more flexible, peaking modes of operation. Furthermore, hydropower infrastructure such as intakes and waterway systems (tunnels, penstocks) may be optimized in order to reduce water and energy losses and thus increase energy production.

3.3 Multipurpose schemes

Multipurpose schemes refer to the use of reservoirs to provide other services beyond electricity generation. Hydropower projects present multiple opportunities to create environmental and socio-economic value for their host communities and regions. Through multipurpose schemes, hydropower reservoirs can contribute to appropriate water management, including water supply, flood and drought management, irrigation, navigation, fisheries, environmental services and recreational activities. Dams have often been built to serve only one of the above-mentioned purposes. However, due to the increasing demand for these services, their spatial and temporal overlaps, the increasing threat posed by climate change and national and international sustainability goals, construction and/or retrofitting of multipurpose dams has been favoured in recent years as they fulfil several purposes within a single facility. Multi-purpose water infrastructure encompasses all constructed water systems, including dams, dykes, reservoirs and associated irrigation canals and water supply networks.

In a multipurpose project a distinction can be made between primary and secondary purposes. The **primary purpose** is the main reason to initiate planning and construction and it largely determines the financial arrangements of a multipurpose dam. **Secondary uses** are planned or attributed as additional functions to make a dam more profitable and have less priority regarding operational management of the reservoir. If hydroelectric power generation is the main purpose, several economic and social benefits can be yielded by adding other uses, including:

- **storing water** during times of high rainfall, to compensate seasonal variation and meet the high water **demand for irrigation** all-year-long;
- providing a **reliable water supply** for municipal and industrial water use;
- using the storage reservoir to **maintain a sufficient channel flow downstream** to allow navigation whilst offsetting seasonal variations;
- exploiting reservoirs for public **recreational benefits**, such as boating, swimming and fishing;
- storing all or a portion of flood waters with controlled release over time to **prevent flooding and drought**.

However, power generation may not be the primary driver for a project. In this case, power generation infrastructure can be added to provide electricity within the constraints determined by the primary use. This is the case for existing non-powered dams and water management infrastructure.

A multipurpose project can be a greenfield project or the result of the upgrading of existing infrastructure. In any case, whilst planning a multipurpose project, it is important to understand the project goals and their relative compatibilities; in fact, the more compatible these different uses are, and the longer and more in-depth the consultations are before commissioning, the easier the management of a reservoir becomes. Three types of conflict may arise from multipurpose projects:

- **conflict in space** may occur if the available volume of the reservoir has to be divided for storing water for divergent objectives. Discussion between all water users will eventually create a consensus between the stakeholders.
- **conflict in time** may arise when water use patterns vary depending upon the purpose, since water releases might be optimal for one purpose, but not for another. In this case prioritization is required.
- **conflict in discharge** appears if the release of water is required for more than one purpose at the same time, and the amount stored is not sufficient for all of them. This is the case when the reservoir purposes are for power generation and other consumptive uses. Since releases for the different purposes may vary considerably during the day, small compensation basins downstream of the powerhouse are used to mitigate the fluctuations in releases to meet varying power demands and help secure water volume for the different consumptive uses.

While multipurpose projects often generate larger economic benefits for the community than single purpose infrastructure, attracting private investors to finance multi-purpose projects is often difficult as they are **less profitable** for them. The reason for this lays mainly in the inherent complexity of dealing with multiple stakeholders. There is a need for **sustainable business models** for both financing, operation and maintenance and the emergence of unforeseen risks and negative externalities.

3.4 Powering non-powered dams

According to the ICOLD register, about 20% of large dams and reservoirs in the world are not used for hydropower generation (Voith, 2017). Powering existing infrastructure shows great potential to increase hydropower generation. Most of this infrastructure is relatively small in size and has low heads. Potential projects require low cost standardized solutions with minimal environmental impact and no need for extensive civil works. Small hydro turbines requiring minimal maintenance, low delivery times and ease of installation are a good options in this case. This technology consists of multiple identical Kaplan bulb turbines in an array facing the water flow. Their advantage is that individual turbines in the array may be retrieved for repair or in case of imminent flood conditions. Also, depending upon the river's discharge at any given moment, different numbers of turbines may be switched on, allowing the discharge through one to be at the optimal level (Hydro Equipment Association, 2015).

4 Infrastructure

4.1 Storage facilities and appurtenant structures

4.1.1 Dam

A dam is a structure designed to retain water from a river. There are two types of dam:

- **diversion dams**, which use diversion systems to keep the water surface at a constant level and avoid changing the river regime. Diversion dams, also called weirs, are used for run-of-river plants, waterways, recreational activities, etc.
- **retention dams** which create a barrier to store water in a reservoir, thus changing the river regime and keeping the water surface at a variable level. Retention dams can be built for two types of reservoirs:
  a. **supply reservoirs**, in which water is extracted from the river for other uses, such as irrigation, navigation, drinking water, industrial use.
  b. **regulation reservoirs**, whose primary function is to regulate water flow. In this case, the water is stored and released into the river for different reasons, such as irrigation, flood protection, drought prevention, compensation of irregular water releases of upstream plants or other uses.

The dam structure is composed of a body lying on a foundation built on the riverbed and the banks of the valley. The dam slopes are called upstream and downstream faces, whilst the crest is the part in-between. There are two main families of dams according to the construction materials used, namely embankment and concrete dams. **Embankment dams** are made of earth or rockfill or a combination of earth and rockfill, while **concrete dams** are built from conventional concrete or from roller compacted concrete (RCC).

Embankment dams are designed by considering different functions, such as water tightness, stability, drainage, protection to erosion and aging, filtration (for embankments), safety including surveillance systems and minimization of environmental impacts. Moreover, the dam design should ensure the capability to withstand accidental loading cases (due to damaged water tightness or ineffective drainage) and extreme loading cases (due to floods or earthquakes of extremely long return periods). Since embankment dams are composed of either earth fill or a combination of earth and rock fill, they are generally built on soft foundations in areas where large amount of earth or rocks are available. They represent 75% of all dams in the world. When the dam is built it is protected from the river by one or two cofferdams. A grouted curtain or diaphragm wall under the core or under the upstream facing is often required to ensure that the foundations are watertight, and it is often combined with a downstream drainage curtain or carpet (Figure 4-1). Waterproofing is often provided by a central part made of compacted earth called a core; in the absence of earth, the core is replaced by an upstream concrete facing (CFRD), upstream bituminous concrete or by a central bituminous wall. The core is surrounded by one or more filter layers to prevent internal erosion. Stability is ensured by shoulders, on either side of the core, made of rockfill, gravel or more resistant earth. A rockfill layer on the upstream facing, called riprap, protects against wave action. Surveillance systems and operating procedures ensure safety. Pore pressure cells, displacement benchmarks and water flow rate weirs are regularly monitored.

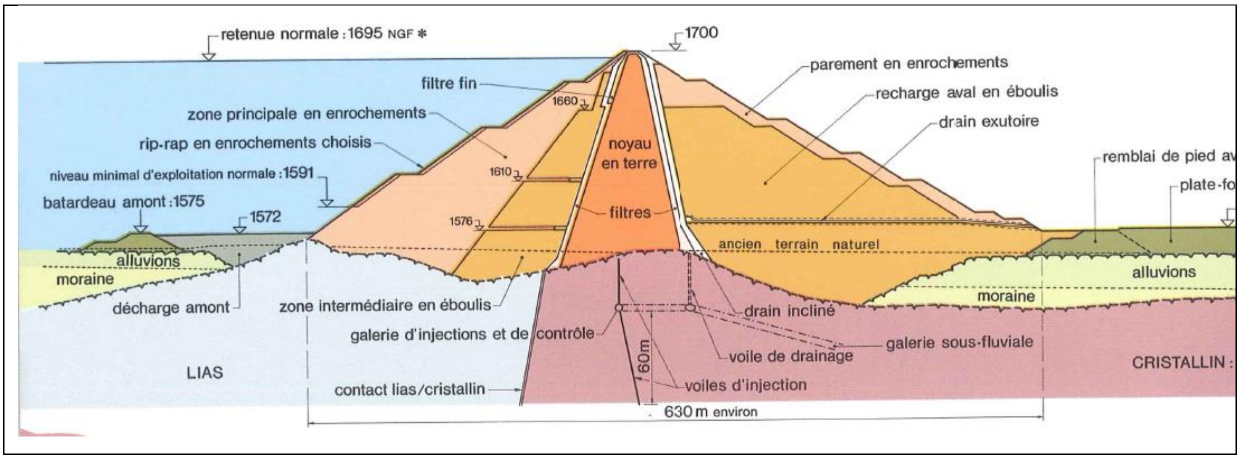


Figure 4-1 Grand Maison dam (EDF) embankment with a core of impervious material

e**Arch dams** are **concrete dams** that curve upstream towards the flow of water. They are generally built in narrow valleys, where the arch can transfer the water force onto the valley sides. Arch dams require much less concrete than gravity dams of the same length, but they do require a solid rock foundation to support the loads. At the base of the dam, a grout curtain reduces the seepage, whilst a drainage curtain reduces the pore pressures and uplift forces. This type of dam is very resistant to hydrostatic and seismic loadings. However, it faces an increasing issue: the ageing of concrete, which cause cracks. A challenge for the coming decades is therefore demonstration of its resilience.

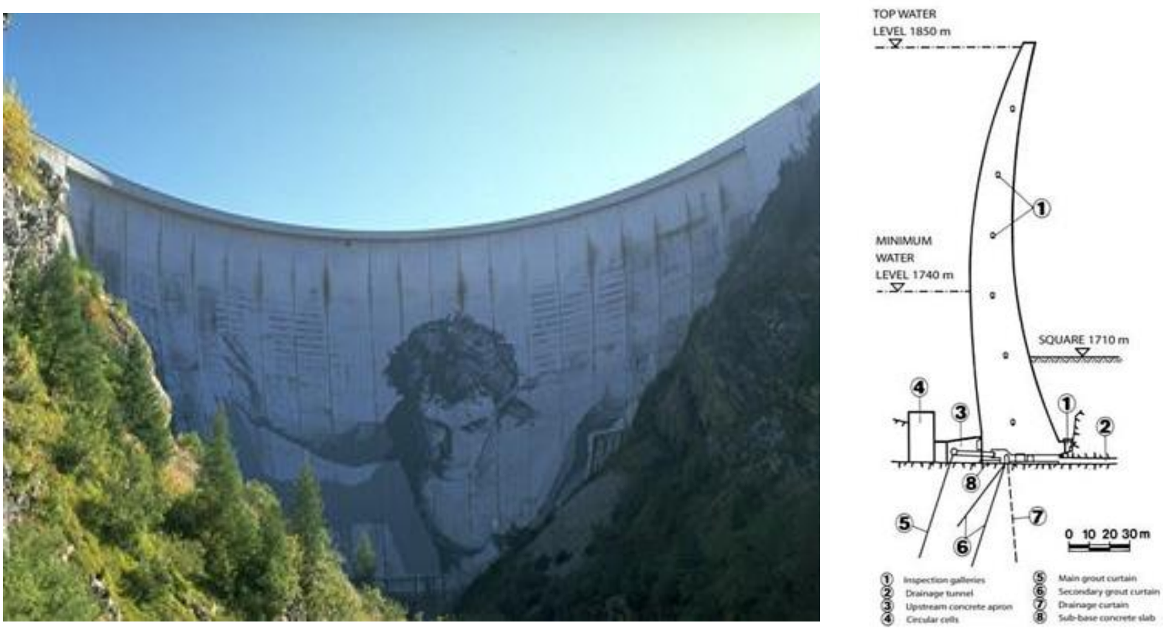


Figure 4-2 Tignes arch dam (left) (Photo EDF) and a typical arch dam section (right)

Gravity dams rely entirely on their own weight to resist the tremendous force of the stored water. In earlier times, some of these dams were constructed from masonry blocks or with buttresses, to save volume. Today, it is cheaper to construct gravity dams by mass concrete, roller compacted concrete (RCC) or Hardfill and cemented soils dams (CSD).

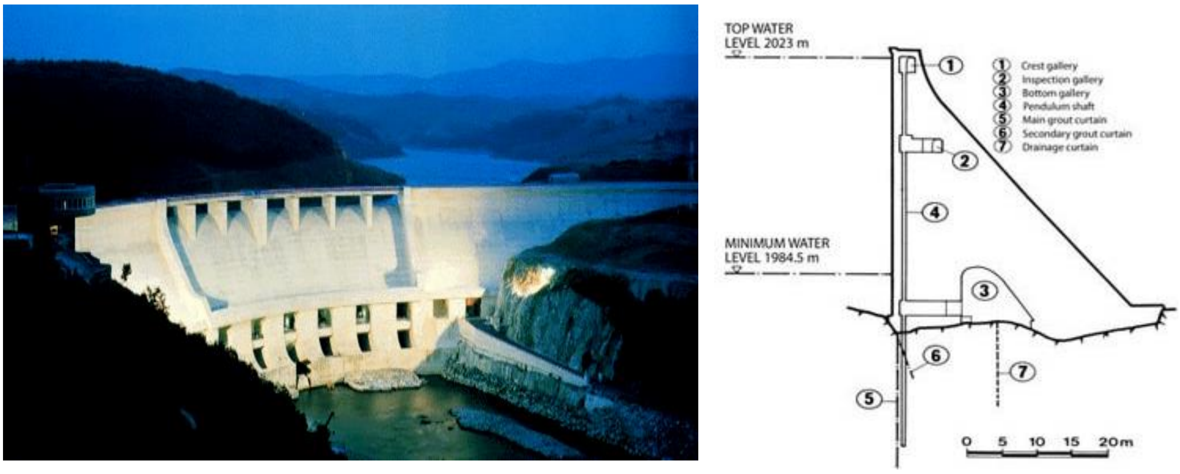


Figure 4-3 Villerest gravity dam (left) (*photo EDF*) *and a typical gravity dam section (right)*

Run-of-river mobile dams are gravity dams built within the river channel specifically for hydropower, taking into consideration navigation needs. They include fixed structures and mobile hydro-mechanical equipment. The structure is a raft that supports concrete piers in the riverbed and abutments on the banks, covered by a manoeuvring bridge. The moving parts are gates located in-between the concrete piers.

Dams are equipped with **appurtenant structures** that allow reservoir water, floods and fish to pass through. These include:

- **diversion structures** (channel, tunnels or culverts) for river diversion during construction in the river channel;
- **intakes structures** for conveying water to the power plant;
- **bottom outlets** for reservoir emptying in case of problems;
- **spillway structures** to control the reservoir level during floods, in order to prevent overtopping and potential failure of the structure;
- **fish passages or elevators** to aid fish migration.

4.1.2 Diversion structures

During construction, the river needs to be diverted to allow construction of the dam in the riverbed. An alternative waterway is built in order to by-pass the dam site and to prevent any damage to the structures under construction in case of a flood. There are two main types of structure: **diversion tunnels** or channels (aqueducts). Although the structures are temporary, a part of them can be used during operation. At the end of construction, they are permanently closed with stop logs or a concrete plug, integrated into the bottom outlet or used as the water intake of the plant.

A diversion tunnel has three parts: the water intake, the tunnel and the outlet. The water intake is a concrete structure designed to yield a smooth flow transition from the river into the tunnel and to impede future clogging. The diversion tunnel or channel is constructed on one bank of the river in order to bypass the dam site. The outlet is either connected to the river or to a stilling basin provided to dissipate excess kinetic energy.

4.1.3 Bottom outlets

Bottom outlets generally perform the following functions:

- controlling the rise of the water body during the first reservoir filling, before the spillway sill level is reached;
- lowering the reservoir level to allow the structure to be inspected and maintained;
- flushing out sediments from the bottom of the reservoir;
- spilling part of large floods as an auxiliary spillway.

Bottom outlets generally consist of one or more steel or concrete pipes crossing through the dam or galleries bypassing the dam through the rocks. They are closed upstream by a guard valve and downstream by a control valve allowing the flow rate to be varied. Downstream, the flow is released into the river via an energy dissipating structure or equipment.

4.1.4 Spillway structures

A **spillway** is a safety structure, designed to control the reservoir level and to release any excess water in a controlled way. The spillway allows flood flows to pass over or around a dam without the structure or its foundations being damaged by submersion or scour, and without the level of the reservoir during flood periods exceeding predetermined levels known as the maximum water level. A spillway essentially has one or two sections: (1) an inlet to guide the flow, and (2) a chute in an open-air channel or a gallery to release the flow (in the case of arch dams, this part does not exist).

The main types of **inlet structures** are:

- **frontal type**, whose overflow across a weir is parallel to the river flow, is the standard and simplest structure, providing a direct connection from the reservoir to the tailwater. It is often used on gravity and arch dams.
- **side channel**, whose overflow across a weir is perpendicular to the river flow, is justified at locations where a frontal weir is not feasible, for example on earthfill dams.
- **shaft type**, whose overflow is radial, could be economical, provided the diversion tunnel is used as the tailrace structure of the shaft. It requires aeration to inhibit vibration, cavitation and air backflow. It could be vulnerable to clogging by debris and trees.

- **orifice type**, used for emptying the reservoir.
- **labyrinth type**, of which the width of free surface flow is 3-5 times the width of spillway, has the advantage of an increased flow capacity compared to a frontal weir for a given reservoir level.

The **chutes** could be:

- a long and smooth spillway (along embankment dams or on abutments), conveying flow with high velocity. Particular attention has to be paid to cavitation due to the very high flow velocity that may generate negative pressures below the water vapour pressure.
- a cascade spillway (on the downstream face of gravity dams), dissipating energy on concrete steps.
- absent, the inlet is the outlet on the crest of an arch dam, inducing a falling nape into a dissipating basin or into the tailwater.

Spillways can be classified according to flow type (free flow or pressurized flow), position (placed on the dam or separated) and flow control (with or without gates).

The **gates** have two functions; in normal operation, the water level is generally maintained at the highest possible level in order to maximize the water head. In flood conditions, the open flow section must be as large as possible. The gates are usually located on the spillway crest for regulation of the reservoir level. The gates are made of welded sheet metal and either mechanically or hydraulically operated. Three types of gates are currently used:

- **radial gates** are the most frequently used on large structures because they are relatively easy to move;
- **vertical gates** require heavy lifting devices and large and resistant mounting slots;
- **flap gates** are used for small heads and a large spilling length. They can be added on the top of radial gates for the fine control of the reservoir level and for the release of well oxygenated surface water.

Gate opening may be a problem in extreme flood conditions, mainly due to jamming with debris, power breakdown or mechanical incident. Consequently, gates must be especially secured against possible failure, ideally operating in a simple and reliable way with power supply backed-up, regularly tested and easy to maintain. The advantages of gated spillways are the fine control of reservoir level, large discharge capacity, higher storage level and higher head on the turbines. The disadvantages are loss of reliability compared to the free weir and additional costs for construction and maintenance. In conclusion, gates are mainly used for large dams, controlling large floods and require larger maintenance teams.

A combination of un-gated and gated spillways, adding the advantages of both, can be achieved through the use of fuse gates. A fuse gate is a concrete or steel component (block, plate, flap) located on the crest dam, which becomes unstable and is flushed away solely by gravity if the reservoir reaches a threshold level. The fuse gate does not rely on a power supply or human action and can be regarded as a very reliable flood control system.

However, fuse gates can generate a significant and sudden increase of the discharge, and they will need to be replaced after the flood.

4.1.5 Dissipation structures

Flow energy is almost always dissipated by a sudden slowing down of the flow and an associated change from super-critical to sub-critical conditions. This is achieved in one of two ways. The whole distance over which flow is super-critical may be canalized, and the change to the sub-critical condition achieved through a structure, such as a stilling basin, where a hydraulic jump will occur. The design of such systems can be undertaken in theory and tested by physical or numerical models.

Alternatively, the turbulent flow may be thrown up into the air above the river channel as a jet or nappe. The change in flow condition occurs in the scour hole or plunge pool that the jet falls into. A scour hole is suitable if it forms naturally with the first spilling and therefore grows slowly enough so as not to endanger the stability of the dam or the nearby valley.

4.1.6 Fish passage technologies

There is a wide variety of fish species, but in terms of their natural mobility they can be separated into three main categories:

- fish that do not leave the river;
- fish that live in the ocean and swim up river to breed; and
- fish that live in rivers and swim down to the oceans to breed.

Structures for fish migration concern upstream migrating fish (such as salmon). There are four types of them:

- fish ladders, for low head dams, comprising an artificial river section with a very slight slope (3 to 5%) are more effective than the older lateral channel design where the water is slowed by transverse walls.
- fish elevators for high head dams comprises a tank equipped with a mechanical lifting system that moves fish from downstream to upstream. Fish are attracted to the tank by the filling current created by the tank.
- fish passes for medium head dams (<30-46m) comprise a succession of pools connected by overflow weirs, vertical slots or submerged orifices, which distribute the head over successive drops of 10 to 40 cm.
- fish locks have two chambers connected by an inclined gallery. Fish move up from the downstream chamber to the upstream chamber by closing the downstream valve.

This topic is further expanded in Section 11.1.

4.2 Water conveyance systems

Figure 4-4 provides a schematic overview of a water conveyance system for hydropower generation (Schleiss Anton 2015).

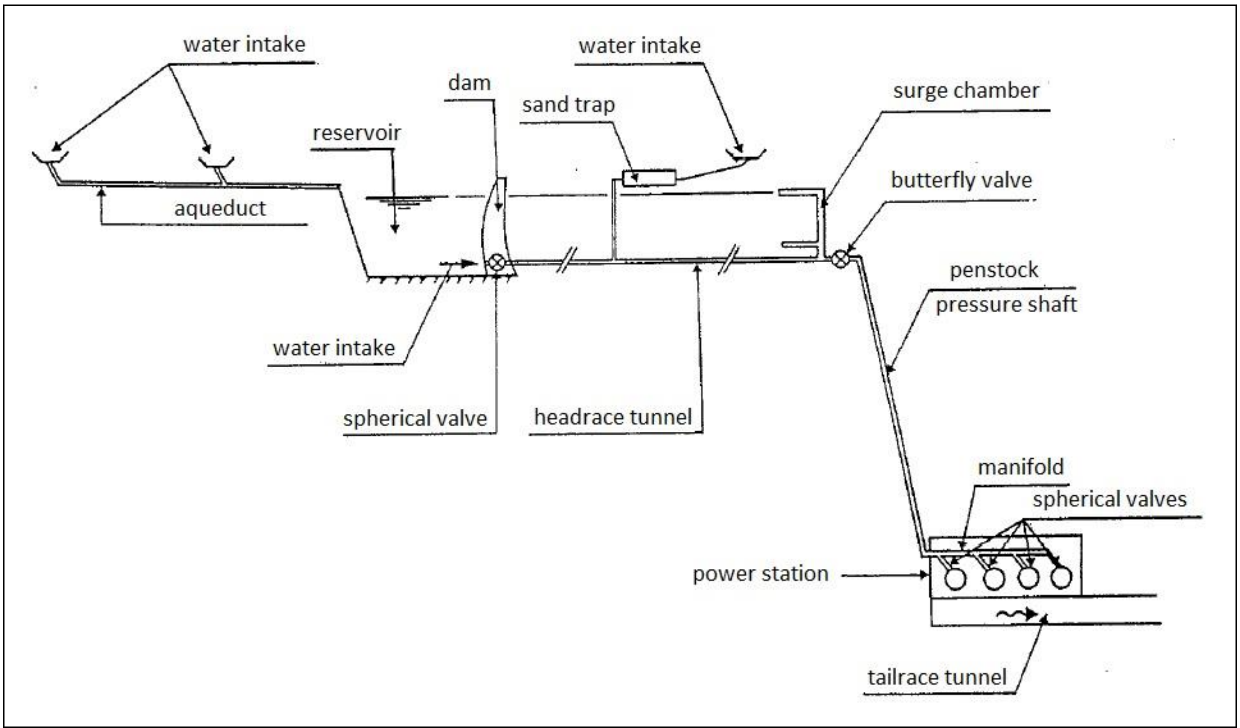


Figure 4-4 Water conveyance system for hydropower

4.2.1 Water intakes

Water intake structures are designed to take water from a river or reservoir to supply the turbines of the power plant, while removing, as far as possible, any solids carried by the water. River intakes generally have three main parts: (1) an inlet designed for maximizing the flow rate, (2) a gate for controlling the flow rate and (3) solids disposal facilities for removing any trash and releasing sediments back into the river. The inlet consists of a concrete structure that directs flow from a sill to the headrace channel or tunnel or penstocks. Water intakes are usually equipped with vertical gates or vertical stop logs used to isolate the system for maintenance. Among the three types currently used, radial gates are the most frequent on large structures as they are easy to move; vertical gates require heavy lifting devices and large and resistant slots, whilst flaps gates are used for small heads and large spilling length. The solids disposal facilities are designed to remove suspended loads (clay and silt), bed loads (gravel and sand) and debris. Debris, such as floating wood, is stopped by log booms and screens. A log boom is a floating cable, stretched across the river, upstream of the water intake. A large mesh screen is located at the entrance to the diversion channel or run-of-river plant. The spacing of the bars is a compromise between protecting fish and limiting head losses. Cleaning of the screens is ensured either by an automatic trash rack cleaner for small bodies or by mechanical shovels equipped with grabs. A gravel basin located just upstream from the reservoir is a basin for catching any gravel. The gravel is cleared annually or after each large flood by a mechanical shovel. A gravel trap is a channel placed laterally at the weir upstream toe, into which any gravel falls. The gravel is discharged by opening a gate that flushes it out. The sand is removed in settling chambers or sand passes. The settling chamber consists of a basin with a flow cross-section significantly greater than that of the headrace channel so that the water velocity drops low enough for the suspended grains to settle to the bottom of the sand pass. The grains deposited at the bottom of the chamber are periodically released into the riverbed through a flushing gallery, by operating a gated orifice. To prevent sedimentation and retention of gravel in a reservoir, a small dam can be built at the reservoir upstream end. The dam will be submerged under flood and sand and gravel will settle behind this dam. A tunnel by-passing the reservoir can be used to transport the sediments downstream of the main dam.

4.2.2 Supply works, headrace and tailrace

Supply works connect a water intake to the penstock inlet of a hydroelectric plant. They can be free surface flow in a channel or gallery, or pressurized flow in a gallery excavated within the rock or built of reinforced concrete in the open air.

If the power plant performs a frequency or power setting function, it must be able to instantly modify the power it supplies, and this is only possible with a pressurized flow in gallery. On the contrary, if the plant follows a predetermined production program, it can be supplied by free surface flow channels. Flow variations are possible in channel by operating the channel feed valves, but they are not instantaneous.

The **tailrace** tunnels or the tailrace channel connect the turbine outlet to the riverbed. It is either outdoor for outdoor plants or in galleries for underground cavern plants. In most cases it is free flowing. The length of the tailrace works depends upon the type of hydropower scheme. For plants located in the riverbed or at the foot of the dam, the length is short, whilst for low head installations whose plant is within a diversion channel, the length of the release channel can be of the same order of magnitude as that of the inlet channel.

The channels have a trapezoidal shape. They are often made in backfill and sometimes they are excavated in the ground. The slopes of the channels depend upon the mechanical characteristics of the materials. The velocity of the water in the channel is designed so as not to cause erosion of the surface material. Reinforced concrete slabs or bituminous concrete pavement improve the strength of the facing and the admissible flow velocity inside the channel.

The galleries can be circular to minimize cuttings or horseshoe shaped to facilitate excavation work. Depending upon the roughness, strength and permeability of the rock, the gallery can be uncoated, covered with shotcrete, ordinary concrete or reinforced concrete. The invert is almost always covered with concrete. If the gallery is very deep, the ground external pressure can become considerable and heavy support is required before concreting the lining. In many cases, the contact between the concrete liner and the surrounding rock is filled with injected cement.

4.2.3 Penstocks, pressure shafts and surge chambers

Penstocks or pressure shafts are pipes connecting the end of the headrace channel/tunnel to the turbines or pumps of a hydropower plant. They experience a pressure close to the drop height. They are made of steel pipes, reinforced concrete and sometimes of plastic or composites. The connection between intake structures and penstocks/pressure tunnels is either made with a surge chimney or by a surge chamber if the intake channel is free flow, to help reduce overpressure due to water hammer in the penstock and in the headrace tunnel, caused by sudden load (flow) changes. The surge chimney is generally a vertical cylindrical tank excavated into the rock.

At the downstream toe of the penstock, just upstream of the powerhouse, the manifold is the pipe that divides the flow into as many penstocks as turbines. Every penstock arriving at the powerhouse is equipped with a butterfly valve or a spherical valve to shut off the flow.

4.3 Powerhouse

A powerhouse essentially includes:

- an **erection bay** used for assembling the turbines and generators before installation;
- an **engine room** (or machine hall) in which all turbines and generators are installed;
- a **basement room** hosting turbines and draft tubes, in case of vertical axis units;
- a **control room** hosting the SCADA (Supervisory Control and Data Acquisition) system, as well as (part of) control, monitoring and signalling equipment;
- a **transformer room** or bay; and
- **ancillary rooms** (electrical rooms, drainage gallery, cooling systems, etc.).

The main equipment in the powerhouse, except the turbines, is the overhead crane used to erect and dismantle the units. The dimensions of the room are determined by the size of the largest piece of equipment to move. Sometimes, the powerhouse height can be reduced by replacing the overhead crane with an open-air gantry crane that operates turbines either outdoor (outdoor plant) or after removal from the plant's mobile roof. When the topography, the geology or the hydraulic conditions are not suitable to install an open-air powerhouse and penstocks on the valley slope, the powerhouse is built within a cavern.

5 Electromechanical equipment

Hydromechanical equipment manufacturers are under strong and growing pressure to innovate. In Europe, the EU's decarbonization agenda is requiring the improvement of hydro equipment, while abroad other manufacturers are threatening to take market share from a sector that is a valuable source of export earnings for the European economy.

The market for large hydropower plants is dominated by a few manufacturers of large equipment and a number of suppliers of auxiliary components and systems. Over the past decades, no major breakthroughs but continuous developments have occurred with the basic machinery; computer technology and digitalization have led to significant improvements in many areas, such as monitoring, diagnostics, protection and control. Operators, manufacturers and suppliers need to invest significant resources into research and development (R&D) to meet advances in operation and technology and to deal with market competition. Also, large hydropower plants may have a considerable impact on environmental and socioeconomic aspects at the regional level. Therefore, the link between industry, R&D and policy institutions is important to the development of this energy sector.

Unlike large plants, small-scale hydropower installations comprise a huge variety of designs, layouts, equipment and materials. Therefore, state-of-the-art technologies, knowledge and design experience are key to fully exploiting local resources at competitive costs and without significant adverse environmental impact.

Upgrading offers a way to maximize the energy produced from existing hydropower plants and may offer a less expensive opportunity to increase hydropower production. Gains of between 5%-10% in production and even more in peak capacity are realistic, cost-effective targets for most hydropower plants. Potential gains could also be higher at locations where non-generating dams are available. Investment in repowering projects, however, involves risks, both technical and legal (e.g. risks associated with the re-licensing of existing installations, often designed several decades ago, with only limited records of technical documentation). As a result, significant potential is left untapped. However, today's technologies allow for a more accurate analysis of geology and hydrology, as well as precise assessments of potential gains.

5.1 Turbines

Hydropower machine, water turbine or hydro turbine are the designations used for a machine that directly converts the hydraulic power in a water flow to mechanical power on the machine shaft. This power conversion involves losses that arise partly in the machine itself and partly in the water conduits to and from the machine.

The specific type of turbine to be used in a power plant is not selected until all operational studies and cost estimates are complete. The turbine selection largely depends upon the site conditions, like water flow and hydraulic head. There is a considerable variety of designs, which are suitable for different applications. Turbine selection should also include a comparison of the relative efficiency of turbine types and their operation under all conditions, especially under reduced flow. Turbines can be divided by their principle of operation:

- **Impulse turbines** are driven by a high-velocity jet (or multiple jets) of water. There are three main types of impulse turbine in use: the **Pelton**, the **Turgo**, and the **Crossflow** turbine.
- **Reaction turbines** have a rotor which is fully immersed in water and is enclosed in a pressure casing. The runner blades are profiled so that pressure differences across them impose lift forces, just as on aircraft wings, which cause the runner to rotate faster than is possible with a jet. The two main types of reaction turbine are the **Francis** turbine (the most common) and the **Propeller** turbine with its variants **Kaplan** (most common), **Bulb**, **Straflo** and **Tube** type. Another type of reaction turbine is the **hydrokinetic** or **free-flow** turbine without any pressure casing and draft tube.

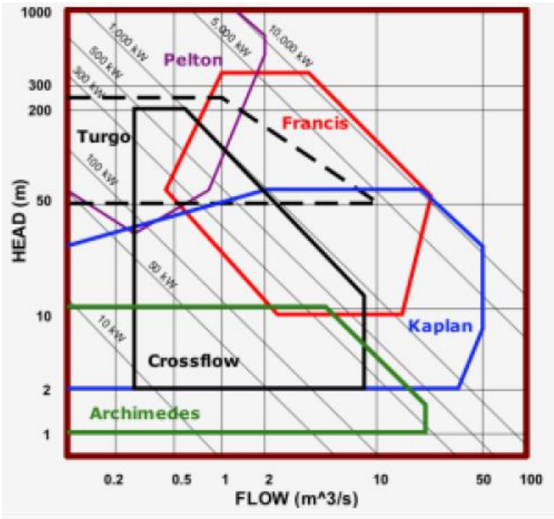


Figure 5-1 Use of turbine types by head, discharge and capacity

- **Gravity turbines** are simply driven by the weight of water entering the top of the turbine and falling to the bottom, where it is released – for example, an overshot **waterwheel** or an **Archimedes screw**. These are inherently slow-running machines.

The approximate range of head, flow and power applicable to the different turbine types are summarised in Figure 5-1 and Table 5-1. These are overlapping and only indicative since in practice this depends upon the precise design of each manufacturer as well as site specific details.

Head classification	Impulse	Reaction	Gravity
High (>50 m)	• Pelton • Turgo	• Francis	
Medium (10-50 m)	• Crossflow • Turgo • Multi-jet Pelton	• Francis	
Low (<10 m)	• Crossflow • Undershot waterwheel	• Alden • Propeller • Kaplan • Francis • Bulb • Straflo • Free-flow	• Overshot waterwheel • Pitchback Waterwheel • Breastshot Waterwheel • Archimedes screw

Table 5-1 Classification of turbines

A water turbine running at a certain speed will draw a particular flow. If there is not sufficient flow in the river to meet this demand, the turbine could start to drain the river and its performance rapidly degrades. Therefore, it either has to shut down, or it has to change its internal geometry – a process known as regulation. Regulated turbines can move their inlet guide vanes and/or runner blades in order to increase or reduce the amount of flow they draw. The efficiency of the different turbines will inevitably reduce as they draw less flow.

A significant factor in the comparison of different turbine types is their relative efficiencies both at their design point and at reduced flows (see Figure 5-2). For example, Pelton and Kaplan turbines retain very high efficiencies when running below design flow, whereas the efficiency of Crossflow and Francis turbines falls away more rapidly if run at below half their normal flow. Over the last century, huge progress was made in turbine development. There has been a trend towards bigger turbine units, higher peak efficiencies and hydraulic performance (better efficiency over the whole operating range (head/discharge)).

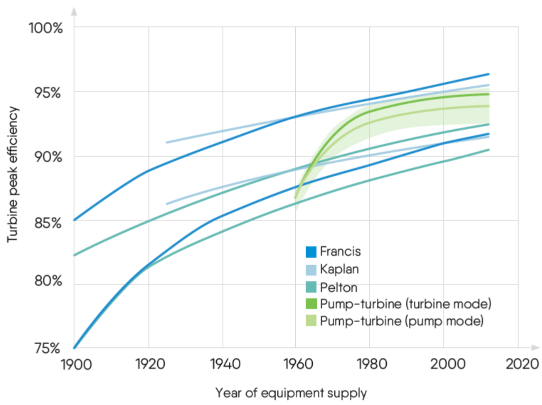


Figure 5-2 Evolution of turbine peak efficiency over the years (source: Eurelectric / VGB PowerTech, Hydropower Fact Sheets, 2018)

5.1.1 Impulse turbines

The impulse turbine generally uses the velocity of the water to move the runner and discharges to atmospheric pressure. The water stream hits each bucket on the runner. There is no suction on the downside of the turbine, and the water flows out the bottom of the turbine housing after hitting the runner. An impulse turbine is generally suitable for high head, low flow applications.

Pelton Turbines

The Pelton wheel is an impulse type water turbine, extracting energy from the impulse of the moving water. The water is directed with high speed through nozzles against the buckets, arranged around the circumferential rim of a drive wheel – the runner. The shaft design can be either in horizontal position in combination with one or two nozzles per runner, or in vertical position with up to six nozzles per runner. Pelton turbines are the solution for high heads up to 1,800 m. Units with outputs up to 800 MW and runner diameters up to 5 m have been successfully implemented.

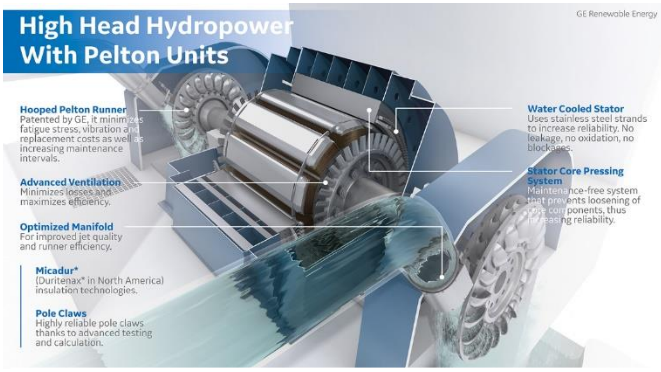


Figure 5-3 Pelton turbine (Source: GE)

The flow simulation of Pelton turbines is by far the most complex and difficult of all hydraulic turbo-machinery simulations. Pelton turbines involve a number of special flow characteristics which are extremely difficult to simulate. The jet-bucket-interaction is fully transient and depends on the moving geometry of the buckets. Even more challenging is the multiphase system of air and water that governs the formation of the free jet and the flow through the buckets. In the past, developing a flow simulation that would allow a realistic analysis of these phenomena seemed to be an impossible task.

A Pelton wheel can have one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Draft tubes are not required for impulse turbine since the runner must be located above the maximum tailwater to allow operation at atmospheric pressure.

Turgo Turbines

The Turgo turbine is a variation on the Pelton turbine, where water does not change pressure but changes direction as it moves through the turbine blades. The water's potential energy is converted to kinetic energy with a penstock and nozzle. The Turgo turbine is similar to the Pelton but the jet strikes the plane of the runner at an angle (typically 20° to 25°) so that the water enters the runner on one side and exits on the other. Therefore, the flow rate is not limited by the discharged fluid interfering with the incoming jet (as is the case with Pelton turbines). Consequently, a Turgo turbine can have a smaller diameter runner and rotate faster than a Pelton for an equivalent flow rate. Turgo turbines are the preferred turbine for hydropower when the available water source has a relatively high hydraulic head at low flow rates. These turbines achieve operational efficiencies of up to 87% (less than the Pelton).

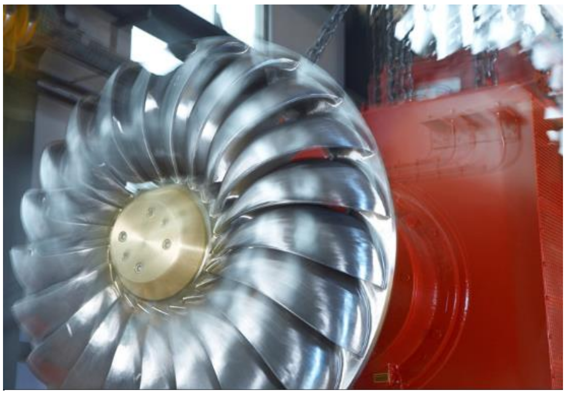


Figure 5-4 Turgo turbine (source: Wasserkraft Volk AG)

The runner is less expensive to make than a Pelton wheel and it does not need an airtight housing like the Francis turbines. Moreover, the Turgo has higher specific speeds and at the same time can handle greater quantum of flows than a Pelton wheel of a similar diameter, leading to reduced generator and installation cost. Turgo turbines operate in a head range where the Francis and Pelton overlap. Turgo installations are usually preferred for small hydro schemes where low cost is very important.

Cross-Flow Turbines

A cross-flow turbine is drum-shaped and uses an elongated, rectangular-section nozzle directed against curved vanes on a cylindrically shaped runner. It resembles a "squirrel cage" blower. The cross-flow turbine allows the water to flow through the blades twice. The first pass is when the water flows from the outside of the blades to the inside; the second pass is from the inside back out. A guide vane at the entrance to the turbine directs the flow to a limited portion of the runner. The cross-flow was developed to accommodate larger water flows and lower heads than the Pelton. The Crossflow Turbine is made for heads of between 2.5 and 200 meters and it is available with outputs of up to 5 megawatts.

The Crossflow Turbine already starts producing energy with a very small quantity of water and deals outstandingly with varying flows. This can be achieved with two cells inside the turbine working independently of each other. Only 5% of the design flow is needed for the smaller cell to start the turbine. Crossflow Turbines are in operation almost all year round, and even when other turbine types have already stopped.

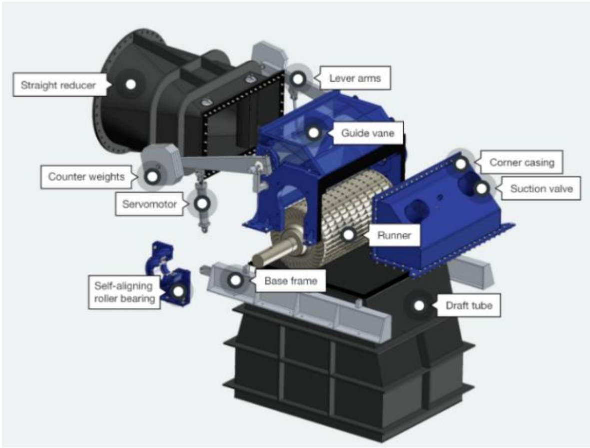


Figure 5-5 Cross-flow turbine (source: Ossberger)

5.1.2 Reaction turbines

A reaction turbine generates power from the combined action of pressure and moving water. The runner is placed directly in the water stream with water flowing over the blades, rather than striking each individually. Reaction turbines are generally used for sites with lower head and higher flows as compared with impulse turbines.

Propeller Turbines

A propeller turbine generally has a runner with three to six blades and the water is constantly in contact with all of the blades. The pressure is constant through the pipe; if it isn't, the runner would be out of balance. The pitch of the blades may be fixed or adjustable. The major components, besides the runner, are a scroll case, wicket gates, and a draft tube. There are several different types of propeller turbine:

- Alden turbines
- Bulb turbines
- Kaplan turbines

Alden Turbines

One of the newest improvements to fish passage technology comes from the development of an innovative runner concept by Alden Research Laboratory. The Alden Turbine features a slower rotational speed and only three blades, in order to reduce fish mortality due to blade strike.

The blade shapes are specifically designed to improve the fish passage environment through the turbines by minimizing shear, pressure change rates and minimum pressures within the water passage. Depending on the species, full-scale fish survival rates are expected to range from 98% to 100%.

Figure 5-6 Alden turbine (source: Voith)

Key benefits of Alden turbines include a reduced strike probability by optimizing the number of turbine blades, wicket gates and stay vanes as well as improving the hydraulic profile of the turbine components and the rotational speed. The turbine also features optimized water passage geometries to meet specified fish passage criteria.

Bulb Turbines

Bulb turbines are suitable solutions for very low head and low output; they have a runner diameter of up to 8.5 m, an output of up to 80 MW and a head range from 0.5 m up to 30 m. The turbine and generator are a sealed unit placed directly in the water stream (see Figure 5-7). The term "Bulb" describes the shape of the upstream watertight casing which contains a generator on a horizontal axis. The generator is in a watertight housing called the “bulb”.

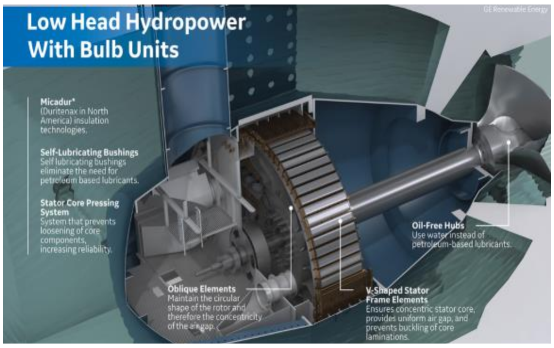


Figure 5-7 Bulb turbine (source: GE)

The application of bulb and pit turbine units has unique advantages. Their design provides good accessibility to various components and assures reliability and a long service life. The most important feature of a bulb turbine is the horizontal positioning of the shaft, in the direction of the flow, which results in reduced size and construction costs compared to a vertical shaft arrangement.

After the intake, the water passes through the moveable wicket gates, which are another device besides the runner for adjusting the water discharge and, as a result, the turbine output. Levers and links connect the wicket gates to the regulating ring, which is moved by two double acting servomotors. After passing the runner, the water exits from the turbine through the draft tube.

Higher full-load efficiency and higher flow capacities of bulb and pit turbines can offer many advantages over vertical Kaplan turbines. In the overall assessment of a low head project of up to 30m, the application of bulb/pit turbines results in higher annual energy and lower relative construction costs. Moreover, with some special design provisions, Bulb units can be operated in pump mode, when rotation is reversed.

Kaplan Turbines

Kaplan turbines are used primarily for lower heads up to 90 m and a unit output of up to more than 230 MW. The degree of efficiency is very high at more than 95 %. The runner diameters can reach up to 10m.

The Kaplan turbine is an outward reaction turbine, resulting in a changed water pressure as the water moves through the turbine and gives up its energy. The runner consists of stainless-steel runner blades mounted on the runner hub and the runner

cap at the lower side of the hub, thus enhancing the optimized hydraulic shape. The runner blades are moveable, allowing adjustment of the water discharge and turbine output (see

Figure 5-8). Due to these moveable blades, Kaplan turbines show a high efficiency level. In some applications, where a (more or less) constant water flow can be guaranteed, the Kaplan turbine can be designed with fixed runner blades.

The Kaplan turbine is often used for run-of-river projects, thus recent design development has been geared towards environmental topics – e.g. the oil-free hub, where the runner hub oil is replaced by water. With a double regulation system (blades and wicket gates are adjustable), Kaplan turbines provide high efficiency over a broad range of configurations.

Figure 5-8 Kaplan turbine (source: GE)

Kaplan turbines are usually designed with a "fish-friendly" structure, to improve the survival rate of migrating species, and water-lubricated bearings and water-filled hubs to prevent water pollution.

Francis Turbines

Francis turbines are used primarily for medium heads and large flows. Their special hydraulic characteristics enable relatively high-speed compact units, right up to the highest power outputs. Francis turbines are the ideal choice for medium head and large unit output. Francis turbines are ideally suited for energy applications with a medium head of up to 700m and an output of up to 800 MW per unit.

The Francis turbine is a reaction turbine where water changes pressure as it moves through the turbine, transferring its energy. A watertight casement is needed to contain the water flow. Such turbines are generally suitable for sites such as dams, where they are located between the high-pressure water source and the low-pressure water exit. Francis turbines are the most common water turbine in use today.

Figure 5-9 Francis turbine (source: GE)

A Francis turbine has a runner with fixed buckets (vanes), usually in the number of nine or more (see Figure 5-9). Water is introduced just above the runner and all around it, and then falls through it, causing the turbine to spin. Besides the runner, the other major components are the scroll case, wicket gates, and draft tube. Runner configuration can be adapted to get the highest level of efficiency in its whole range of application.

The result of product evolution is the ring gate solution, a cylinder that moves between the stay vane and the guide vanes and can replace the traditional butterfly or spherical valves. This technology results in reduced maintenance costs and increased safety, while increasing plant efficiency.

Francis turbines are available in varying configurations, horizontal or vertical, with flexibility in design to ensure best efficiency and reliability of operation under the most extreme conditions. Francis turbines are characterized by incomparable longevity, durability, reliability, and robustness. Extensive research and development activities ensure best efficiency and maximum output over a wide range of operations, both in multiple and single unit configurations.

Hydrokinetic/Free-flow Turbines

A hydrokinetic turbine is an integrated turbine generator to produce electricity in a free flow environment. It does not need a dam or diversion. These turbines use the flow of water to turn them, thus generating electricity for the power grid on nearby land. Therefore, they can be placed in rivers, man-made channels, tidal waters, or ocean currents.

5.1.3 Pump hydro turbines

Pump turbines can reverse the water flow and operate as a pump to fill a higher storage reservoir in off-peak periods, and then revert to a classical water turbine for power generation during peak demand.

The multitude of configurations available include horizontal or vertical, single or multiple stage, fixed or variable speed, with or without cylindrical ring gate, and individual or combined actuation of the guide vanes. Pump turbines, usually based on the Francis type, are custom designed to meet the most demanding requirements and environmental criteria in pump storage applications worldwide. With some special design provisions, Bulb units can also be operated in pump mode, when rotation is reversed.

Pump turbines can cope with rapid mode changes and are ideally suited for generation as well as storage of energy, whilst helping to stabilize electrical grid fluctuations. Fast start-up times of just 90 seconds for up to 400 MW allow for an increased number of daily starts and stops, adding flexibility and availability.

This pumped storage technology can switch between pumping and generating modes within 20 to 30 seconds. This can be achieved thanks to fixed speed reversible units, variable speed pump turbines or ternary pump turbine units. This format offers the largest scale electricity storage technology with the shortest reaction time.

5.1.4 Gravity turbines

Archimedes Screw

Archimedes screws are used to pump large volumes of water at relatively low heads and is extremely reliable and durable. The Archimedes Screw has been used as a pump for centuries but has only recently been used in reverse as a turbine. It's principle of operation is the same as the overshot waterwheel, but the shape of the helix allows the turbine to rotate faster than the equivalent waterwheel and with a high efficiency of power conversion (over 80%).

Figure 5-10 Archimedes screw

However, Archimedes screws are still slow-running machines, which require a multi-stage gearbox to drive a standard generator. A key advantage of the Screw is that it avoids the need for a fine screen and automatic screen cleaner, because most debris can pass safely through the turbine. The Archimedes screw is proven to be a 'fish-friendly' turbine.

5.2 Generators, transformers and high voltage equipment

Generators convert mechanical energy from the turbine into electrical energy using an excitation system. Generators are characterized by their compact design, high efficiencies, and long lifetime, thanks to the use of modern generation methods and optimized manufacturing procedures and materials.

Depending on required runner speed and power station characteristics, generator types can be classified as follows:

- **Horizontal** vs **vertical**: hydro generators are classified by their axis location.
- **Brushless excitation** generator with rotating exciter machine vs **static excitation** with sliprings and brushes.
- **Synchronous** vs **asynchronous generators**: **synchronous generators** (the usual type) are equipped with a DC electric or permanent magnet excitation system, associated with a voltage regulator that controls output voltage before the generator is connected to the grid. Synchronous generator excitation is independent of the grid, so synchronous generators can build up voltage even without grid connection. **Asynchronous generators** are unable to regulate voltage output and are mechanically driven at a speed higher than system frequency (synchronous speed); if isolated from the grid they cannot produce power because their excitation energy comes from the grid.

The choice of **generator inertia** is an important consideration in the design of a hydroelectric plant. The rise speed of the turbine-generator unit after a sudden load rejection, caused by the instantaneous disconnection of electrical load, is inversely proportional to the combined inertia of the generator and turbine. In addition, inertia of large hydro units is a valuable contributor to frequency stabilisation within the power network. This is of growing importance, as increasingly volatile renewable energy sources like PV cannot provide inertia whilst the share of big thermal based sources is decreasing.

Synchronous generators and **induction generators** are used to convert mechanical energy output from the turbine into electrical energy. Induction generators are used in small hydroelectric applications (less than 5 MVA) because of their lower cost, which arises from elimination of the exciter, voltage regulator, and synchronizer associated with synchronous generators. The induction generator draws its excitation current from the electrical system and thus cannot be used in an isolated power system.

Large hydro generators are **customized** for each project, to ensure enhanced performance for site conditions and operators' needs. Each large hydro generator is engineered to run smoothly under any operating condition, whilst reducing structural stress and improving reliability for the lifetime of the turbine.

5.2.1 Vertical shaft generators

Vertical shaft generators are coupled to vertical shaft hydro turbines of any size with outputs up to 840 MVA. There are examples of vertical generators using Francis, Kaplan and Pelton turbines for the whole range of outputs and speeds.

5.2.2 Pit type generators

Pit type generators are used for smaller, low-head applications and are coupled via step-up gear to the horizontal turbine shaft. Pit applications are an economical solution for low-head hydropower stations with lower ratings (typically up to 17 MVA and with 500 to 900 rpm). Pit generators provide a robust design and cope reliably with the high runaway speeds required for hydropower plants. Cooling systems evolved from originally separate heat exchangers to maintenance-free closed loop systems and provide heat dissipation directly into the river water passing the bulb unit. For very high capacities and high-speed units, pressurized air can also be used to improve heat dissipation.

5.2.3 Motor generators

Motor generators are used in pumped storage plants to generate electrical energy and to drive pump turbines. Motor generators for pumped storage applications reach up to 360 MVA with constant or variable speed and one or two directions of rotation. They can be coupled with all unit configurations, for example fixed coupling to reversible pump turbines or turbine-plus-pump (ternary) sets. For starting the units from standstill in pump mode, speed/frequency needs to be smoothly increased from zero to a synchronous speed. The units can be started with static frequency converters (SFC), a pony motor, a start-turbine, or back-to-back (where the generator of a second unit in generator mode works like a variable frequency supply).

5.2.4 Variable speed motor generators

In conventional plants, the rotational speed of the generator/motor and turbine/pump must be constant in order to keep synchrony with the grid frequency. Under these conditions the provision of ancillary services to the grid is limited. Moreover, in the case of pumped-storage plants, operation at a constant speed does not allow adjustment of the pumping power, thus preventing optimal use of surplus energy. Variable speed motor generators allow these issues to be overcome by changing the rotational speed in response to the grid's needs. In other words, they increase the controllability of the power system by offering high dynamic control. See more detail on this in Section 6.3.

5.2.5 Transformer and high voltage equipment

Hydro power plants, as other power plants, need power transformers and high voltage equipment, such as circuit breakers, disconnectors, busbars and cables to transmit electricity to the grid. These devices are not specific to the hydro market. Significant efforts are aimed at improving durability, minimising environmental impacts and reducing fire risk as well as adapting them to eco-design or grid code requirements.

The first concern regarding transformers is to improve their safety regarding fire risk. Feedback analysis and investigations of the transformer fleet and other electrical equipment has been undertaken to gain a better understanding of the risk of failure. Recent developments involve monitoring systems that provide real time information about the operating conditions of the equipment. For example, online gas analysers are installed on power transformers to detect problems and help prevent failures.

From an environmental perspective, ester insulation is preferred to the use of mineral oil. Benefits of ester insulation are high flash and fire point for increased safety, readily biodegradable liquid for extended environmental protection and high moisture tolerance for a long lifetime. Another main issue is the reduction in the use of SF6 greenhouse gases for circuit breakers and gas insulated busbars. Developers are testing new insulating gas and promoting vacuum circuit breakers instead of using SF6 circuit breakers.

In hydro power plants efforts are focussed on the reliability of transformers and high voltage devices in order to maximize their availability and to fit specific operating conditions, coping with more numerus starts and stops in pump storage power plants. New calculation tools allow manufacturers to optimize their design as a trade-off between different aspects: specified guaranties of the losses, mechanical requirements (short circuit), dielectric requirement, thermal requirements, but also space restriction for the transport and civil work installation.

5.3 Hydraulic steel structures

Hydraulic steel structures are installed in hydropower plant schemes to control water flow using gates or valves, which are classified according to their operational purpose:

- **service gates** for continuous flow regulation in the waterway or of the water level in the reservoir, include spillway gates, bottom outlet gates, and lock gates (for navigation).
- **emergency gates** are used to shut down water flow in conduits or open channels; typically, they are designed only to be fully open or fully closed and they include intake gates, gates upstream of penstock service valves, draft tube gates, and gates installed upstream of bottom outlet gates.
- **maintenance gates** are used to empty the conduit or canal for equipment maintenance (turbines, pumps or other gates); the most common type is the stoplog gate. Distributor vanes or turbine needle valves are used for flow regulation.

5.3.1 Gates

The most commonly used gate types are flap, cylinder, stoplog, slide, caterpillar, mitre, roller, segment, sector, drum, fixed-wheel and visor. Each gate type is unique in terms of purpose, movement, water passage, leaf composition, location and skin-plate shape. Gate type selection depends on purpose, dimensions of the opening to be gated, climatic conditions (e.g. passage of ice slabs) and options for gate operation. There are several types of gates:

- Radial Gates
- Wheel Gates
- Slide Gates
- Flap Gates
- Rubber Gates

5.3.2 Valves

Valves fulfil various important tasks: from safety enhancement in powerhouses or penstocks to tight sealing in waterways for maintenance purposes on hydraulic machinery. Hydropower makes an indispensable contribution to the safe, environmently friendly generation of electric power. The fate of both today's world and of the future depends upon having a secure energy supply from hydropower plants that are dependable and operational at all times. Safety remains in the foreground when it comes to hydropower plants. Valves and shut-off equipment that are dependable and durable play a vital role to that end.

The function of the penstock and main inlet valves is to isolate the unit and completely cut-off the water flow at the location where such valves are installed. They usually serve as a safety device and are capable of closing at the maximum water discharge. Main inlet valves are positioned between the penstock and the turbine spiral case, while the penstock valves can be located anywhere inside the penstock. To prevent significant damage in the event of a rupture of the penstock, a pipe break valve is normally installed in the pipe just downstream of the shut off valve. These valves close automatically when the water velocity exceeds a certain set value. They exist in different types and design depending upon function and requirements. The most relevant types of valves are:

- Spherical valves
- Butterfly valves
- Gate valves
- Ring valves

Spherical Valves

Spherical valves are used as safety and shut-off equipment for turbines and pumps in conditions under high operating pressure. Spherical valves are presently covering a pressure range of 160 m to 1,250 m water head. They are used as pipe brake valves as well. They close automatically without the need for outside energy, even against unidirectional pressure at maximum flow rate.

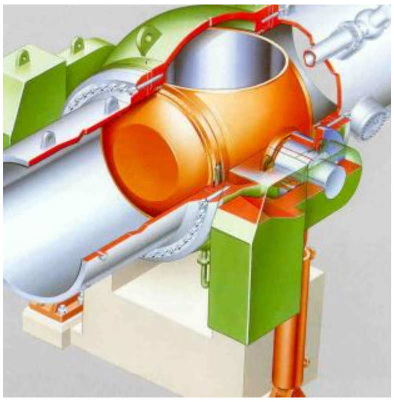


Figure 5-11 Spherical valve

The spherical valve consists of the valve housing with flanges, valve rotor, bearings and seals. Spherical valves are welded constructions or forged using high quality steels. They generally have two sealing systems. The inspection seal ring facilitates maintenance work without having to empty the pressure line. The operating seal ring – taking the place of a bypass – is also used for filling the turbine housing.

The spherical valve can be opened and closed via weight, feed water or oil hydraulics. The feed water for actuating the gaskets is sourced from the penstock and fed to the hydraulic control system via suitable filters.

The hydraulic servo drive and the counterweight are flanged directly onto the valve body and do not require any additional anchoring. End position dampening equipment facilitates optimum closing characteristics to prevent water hammering.

The opening and closing operation of the valve is carried out by one or two servomotors. Since the valve is designed to close against the flow at full turbine load, the valve rotor is subject to a large torque. This torque is transferred to the valve housing through the foundation of the servomotor. Therefore, the total closing torque is absorbed by the pipe and the valve.

Butterfly Valves

Shut-off and butterfly valves are suitable for use as safety equipment in emergency shut-off situations and deliver absolute reliability in case of a penstock rupture. Butterfly valves are normally applied in front of low and medium head water turbines, i.e. heads up to 200 m.

For high head power plants, the butterfly valve is from time to time used as a closing device in inlet tunnels and alternatively as emergency closure valves. Butterfly valves consist of a ring-shaped housing, the valve disc, operating mechanism and counterweight. Butterfly valves protect against rupture and may be placed at the intake, in the headrace line or at the start of the penstock. Butterfly valves are optimally suited to critical situations and stand out due to their performance and low-pressure loss, with absolute impenetrability under all operating conditions.

As discs are moulded to match flow direction, there is minimal pressure loss. Both single- and double- decker (bi-plane) structures are used, depending on nominal diameter and operating pressure. Stainless steel sealing strips in combination with replaceable valve seals guarantee a seal in all operating situations. The self-lubricating bearings are maintenance-free and the bearing seals can be replaced from the outside.

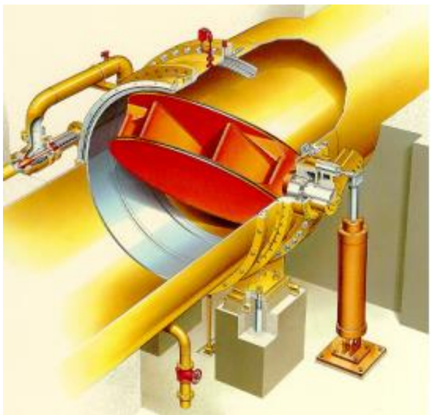


Figure 5-12 Butterfly valve

The hydraulic servo drive and counterweight are flanged directly to the valve housing and do not require any additional anchoring. End position dampening equipment facilitates optimum closing characteristics to prevent water hammer within conduits.

The butterfly valve shall be able to open and close under equalized water pressure on the disc sides, as well as at full turbine discharge. In addition, emergency closure valves shall close automatically in the case of penstock rupture.

Axial Piston Valves

Axial piston valves are the optimal solution for controlled pipe filling, even under extremely high pressure, and can also be used as a control valve for starting up pumps. Made of stainless steel, they are characterized by their longevity and high level of availability. The interrupted water jet and bent position prevent a wash out of the corrosion protection in the area of the water jet inlet. Operation is done either with water or oil hydraulically via an electronic positioner. Additionally, the valve position is visually displayed on a scale. Gate valves are ideal as hand-operated shut-off valves under low pressure. Based on the specific requirements, gate valves can be provided in stainless steel.

Figure 5-13 Axial piston valve

For opening and closing of the valve the operating mechanism may be hydraulic, electrical or manual. On larger valves it is natural to use hydraulic control due to the large forces involved. For the hydraulic operation, water pressure from the penstock or oil pressure from a hydraulic power unit is used. If water pressure from the penstock is used, the cylinder wall has an inner layer of rustproof material. In this case the piston normally has a leather gasket against the cylinder wall. The water must pass a filter and be carefully cleaned before entering the cylinder. For smaller, remote-controlled valves, electrical operation is an alternative.

Ring Valves

Ring valves have been used in many types of hydro power applications. In pump storage plants they are the most applied valve for closing the outlet of the pumps. However, they are also applied as pipe break valves, drain valves and safety valves.

Figure 5-14 Ring valve

Ring valves consist of a piston shaped closing device which is moved axially when opening and closing. The valve housing is partly conical and partly cylindrical, and together with the closing device it forms a ring-shaped flow cross section.

The closing device is supported in the housing by ribs. The closing device consists of a piston with piston rod connected to a cylindrical member. This member has a seal ring fastened to the downstream end of it. The seal ring is made of stainless steel and designed to adapt to the housing seal ring in the closed position. The piston and piston rod are centred by a bushing at each end.

Ring valves installed in drain conduits are equipped with an auxiliary valve upstream and a pressure reducing device downstream of the ring valve. The pressure reducing device is an energy dissipator connected with the downstream end of the ring. The energy dissipator consists of concentric plates with a large number of small axial holes. By this arrangement the pressure drop at any point is kept below a level where cavitation may occur. For heads lower than 75m ring valves are delivered without a pressure reduction device.

Needle Valves

Needle valves are the ideal type of valves when the aim is to safely regulate pressure heads or flow rates, for example, as ground sluice of water reservoirs or in the inlet, the bypass or the secondary outlet of turbines. For this purpose, the cross-section of the internal valve body is constricted by an axially movable piston, thus changing both the pressure and the quantity of flow and velocity. This induces high stress onto the valve, which the needle valve will be able to cope with in the long run.

Figure 5-15 Needle valve

Safe energy transformation without cavitation damage is enabled thanks to the ring-shaped cross-section existing in every position. Depending on the application field, further control inserts, such as vaned rings, slotted cylinders or perforated cylinders are also available apart from the standard seat ring. A range of drive options (electric, pneumatic, hydraulic or weight-loaded) complete the system.

Bypass Valves

A bypass valve is the opening / closing device in a pipe connecting the upstream and downstream side of the valve in the main conduit. This bypass is used to equalize the pressure on the two sides of the main valve, in order to relieve the valve from large loads during normal opening and closing. The bypass is also used to fill the scroll casing of Francis turbines and the distribution pipe of Pelton turbines. Opening and closing times are determined by orifices in the supply pipes to the servomotor.

Figure 5-16 Bypass valve

Hollow Jet Cone Valves

In hydropower plants, irrigation dams, compensating reservoirs or detention reservoirs, hollow jet valves are used for environment friendly discharge of water downstream or into a tailwater pool. The water is simultaneously enriched with oxygen in this process. The high quality structure facilitates cavitation and vibration free energy dissipation.

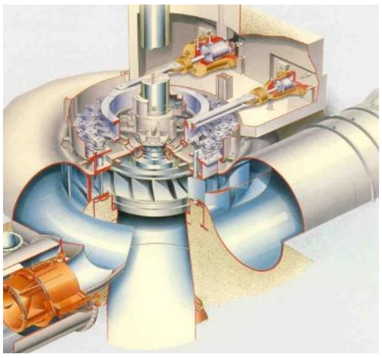


Figure 5-17 Hollow jet cone valve

Hollow jet valves are made from high quality steel in combination with an elastic/metal seal and an integrated jet deflector.

Electric and hydraulic operation allows excellent control performance. Electric heaters for use in cold climates and other specific customer requirements can be implemented. The control system can be designed in such a way that the control room can recognize the cylinder‘s position at all times. This allows a precise control of the discharge rate.

Pressure Relief Valves

Pressure relief valves are used to prevent mechanical over rev and a high increase in pressure when there are short closing times on turbine inlet nozzles or turbine guide vanes. When a stop command is sent to the turbines, they open immediately and simultaneously and – as a by-pass – re-route the corresponding volume of water directly into the tailwater pool. Then the pressure relief valve is closed for the predefined time frame.

Figure 5-18 Pressure relief valve

Pressure relief valves are built as poppet seat valves with an opening tendency and hydraulic drive. The optimal form for the water-guidance components is crucial for operation and is designed to be free from cavitation and vibration as much as possible.

The housing and inlet elbows are made from high quality steel, while the gaskets and the pistons are made from stainless material.

5.4 Penstocks

Penstocks supply one or more hydraulic units with high pressure water. Penstock engineering and construction involves different disciplines like civil engineering and pressure vessel making. There are three main types of pipe installation:

1. **overhead pipes**: whether external or placed in a gallery, pipes are placed on supports. The pipe bends can either be blocked (in a concrete anchor bed, or a mixed concrete-steel bed) or free.
2. **buried pipes**: placed in a trench which is then backfilled.
3. **pipes supported by the rock**: pipes are underground, placed in inclined or vertical shafts and attached to the rock with concrete.

The choice of design is based on studies, where population and vegetation considerations could be as decisive as geological and geotechnical parameters. The design of penstock uses common principles, rules and recommendations, but there is no standard product. The final design must be the result of a technical-environmental-economic study including geological, topographical and environmental aspects, the number of penstocks according to the number of machines, diameter, length, pressure, available technologies, civil engineering/piping balance, etc.

Equipment related to penstocks includes:

- bifurcations, distributors, collectors and manifolds for feeding several turbines;
- traps, air vents for removing air and reducing turbulence;
- vents or suction cups for draining water;
- manholes for access;
- removable cuffs and expansion joints for balancing thermal expansion and dropping thermal stresses; and
- monitoring systems measuring overspeed or overflow, strain, stress, water pressure.

The design of penstocks has evolved with technological developments. Currently many penstocks in operation have been manufactured using technologies that have now been abandoned, such as riveted steel pipes, steel pipes welded with gas and water, self-fretted or hot-fretted steel pipes, pipes with forged collars, pipes with cable straighteners, pipes with self or hot shrink-wrapping. This poses a maintenance problem since the previous methods are no longer used with the advent of thick welding technology on site. Today, we can use "high yield strength" steels, which are tempered or thermomechanical steels, with elastic strength characteristics up to 690 MPa. Other cheaper materials are also used including: concrete, reinforced concrete with or without sheet metal core, reinforced concrete with participating sheet metal, ductile iron, PVC, HDPE and GRP.

6 Flexibility in power generation and storage

6.1 Balancing and ancillary services of hydropower

If large fluctuations of voltage and frequency occur, they can lead to blackouts and damage electrical devices and facilities. The increasing penetration of renewable energy in the power grid poses new challenges to the stability of the system. The main strength of hydropower is the fact that it can serve as a dispatchable, responsive source of bulk power; therefore, hydropower generation can substantially contribute to stabilising the grid. Pumped storage plants can additionally serve as controllable loads, drawing electricity from the grid to recharge their reservoirs when excess energy is available. For these reasons hydropower is more and more used to provide ancillary services to the grid, including:

- **Balancing services**, such as frequency control, spinning reserve and energy storage. Frequency control can be provided by hydropower through different mechanisms, namely: a) inertia (a passive response due to rotating masses in generators), b) primary frequency response (active, unmanned response implemented through an electronic, digital, or mechanical device) and c) frequency regulation (active response to adjust generation to maintain interchange schedule and frequency). Spinning reserve offers generation that is reserved to quickly respond to system events by increasing or decreasing output; hydropower offers an excellent source of reserve because it has high ramping capability throughout its range. In addition, water storage allows the power system to balance variability existing in the load over longer timeframes than the frequency response, from multiple minutes to several hours.
- **reactive power**: hydropower facilities are operated to follow a voltage schedule to ensure sufficient voltage support.
- **black start**: thanks to the capability of many hydropower plants to start their generator units without the need for external power from the grid, these are best suited to provide restoration of an electricity network after a black-out.

To provide balancing power, hydro plant operators need to ramp-up and ramp-down production faster and more often, as well as frequently start and stop power generation. Flexibility in power generation and storage is defined here as the capability to increase the operation range, both in generating and pumping mode, allowing the power plant to operate at deep .importance given to the peak efficiency of individual plants is declining relative to their ability to support the grid. Their capability to function well at deep part-load both in generating and pumping mode is becoming more and more important.

Pump-storage hydropower (PSH) is best suited to offer balancing services to the grid. Classical pump storage arrangements are based on four machine solutions, including a pump, a motor, a turbine and a generator. More efficient solutions are based on reversible fixed-speed turbines. Reversible units can rotate in two different directions, depending on their mode of operation. They have a load range for generation between 50% and 100% of total power. However, power control is not possible in pumping mode as they can only operate at fix-speed. Ternary set systems and variable speed technologies offer significant benefits in terms of flexibility.

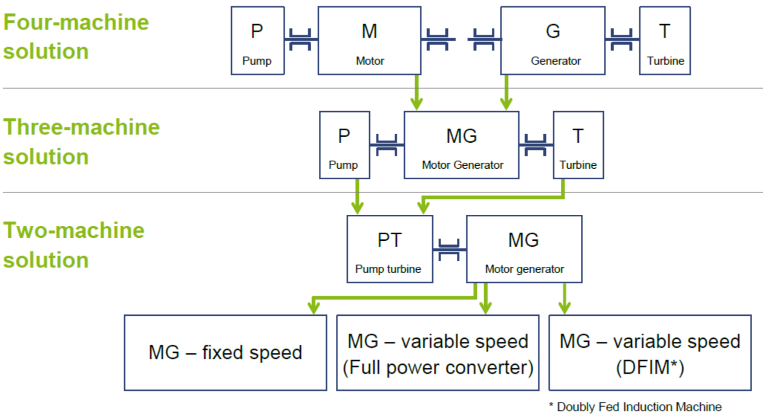


Figure 6-1 PSP Solutions for balancing services (Source: Voith)

Capability	Fixed-Speed PSH	DFIM Adjustable-Speed PSH	Ternary PSH with Hydraulic Bypass and Pelton Turbine
Generation Mode:			
Power output (% of rated capacity)	30%[a]–100%	20%–100%	0%–100%
Standstill to generating mode (seconds)	75–90	75–85	65
Generating to pumping mode (seconds)	240–420	240–415	25
Frequency regulation	Yes	Yes	Yes
Spinning reserve	Yes	Yes	Yes
Ramping/load following	Yes	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Generator dropping	Yes	Yes	Yes
Pumping Mode:			
Power consumption (% of rated capacity)	100%	60%-100% (75%-125%)[b]	0%–100%
Standstill to pumping mode (seconds)	160–340	160–230	80
Pumping to generating mode (seconds)	90–190	90–190	25
Frequency regulation	No	Yes	Yes
Spinning reserve	No	Yes	Yes
Ramping/load following	No	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Load shedding	Yes	Yes	Yes

Figure 6-2 Capability of PSH solutions (DOE, 2017)

6.2 Ternary set systems

Ternary set systems allow the transition time to be significantly reduced compared to conventional reversible turbines. A ternary set consists of a separate turbine and pump on a single shaft with an electric machine that can operate as either a generator or a motor. Depending upon the hydraulic characteristics of the site, the turbine can be of either the Francis or Pelton design (usually the Pelton design is used for installations with very high head). This configuration allows for the same rotational direction of the motor-generator in both operational modes. A clutch operable at standstill, a starting turbine or a synchronizing torque converter enable switching the machine between turbine and pump operation.

This configuration also makes it possible to implement the so-called "hydraulic short circuit" within the machine set, which allows the unit to generate power at the same time as it is pumping water for storage. This allows for an immediate response to changing energy needs. A further advantage of ternary units over reversible pump-turbines is improved efficiency. While in a reversible unit the design is optimized to allow for operation as either a pump or a turbine, in a ternary unit both the pump and the turbine can be optimized for efficiency. However, the ternary design entails some disadvantages, including:

- higher upfront costs because the hydraulic design is more complex and because more equipment is required;
- need for larger hydropower plants because of the additional equipment;
- slightly higher operating and maintenance costs due to the additional equipment.

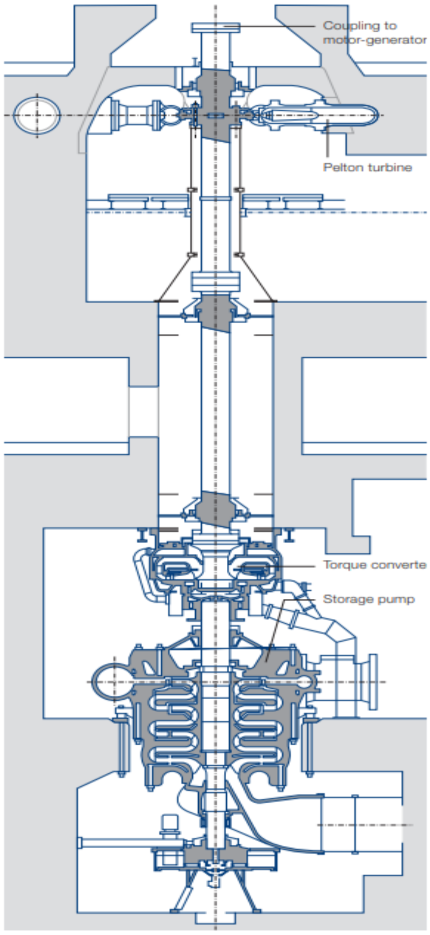


Figure 6-3 Configurations of a ternary set system

6.3 Variable speed operations of PSH

In conventional hydropower plants, the rotational speed of the generator and turbine must be constant in order to produce the grid frequency. Under these conditions the provision of ancillary services to the grid is limited. Moreover, in the case of pumped-storage plants, operation at a constant speed does not allow for adjusting the pumping power, thus preventing the optimal use of surplus energy. Variable-speed hydropower generators (motor–generators in pumped-storage facilities) allow these limitations to be overcome by changing the rotational speed in response to the grid's needs. In other words, they increase the controllability of the power system by offering high dynamic control.

Variable-speed units also operate with greater overall efficiency than fixed-speed units, especially when generating at partial load. This efficiency increase occurs because the rotating speed can be optimized for a given head and rate of water flow through the turbine. Depending upon the design, variable-speed units may have a narrower rough zone and the ability to generate at lower power levels.

Another advantage of variable-speed technologies is the electronically decoupled control of active and reactive power, which provides more flexible voltage support for the system.

Variable speed hydropower generation solutions have become popular for pumped-storage hydropower plants. As a matter of fact, conventional pumped-storage facilities with constant rotational speed are not able to provide the high degree of flexibility required by the power system. In order to stabilize a power grid with high levels of variable energy sources, pumped-storage plants need to be able to quickly switch from generating to pumping mode and vice versa.

The variable-speed operation of pumped-storage hydropower plants can bring additional flexibility to the power system while offering a variety of valuable ancillary services. Whilst in conventional hydropower plants the turbine governor has the function of controlling output power, in variable speed system this task is performed by the converter. This results in faster and higher dynamic power control that can be used to improve power system stability, for example by instantaneous power injection (since the rotational speed does not need to be constant, a large amount of active power can be injected into the grid by reducing the rotational speed). Another significant advantage of variable-speed operation is the ability to control power in pumping mode, thus contributing to frequency control, both in pumping mode and in generating mode. Variable-speed pumped-storage plants are also able to compensate for the production of variable renewables and improve their integration into the grid. In fixed-speed systems the pumping power cannot be regulated and the only way to increase flexibility is to use multiple pumps. However, in this case, the capability for load balancing is lower and frequent start/stop sequences imply higher maintenance costs.

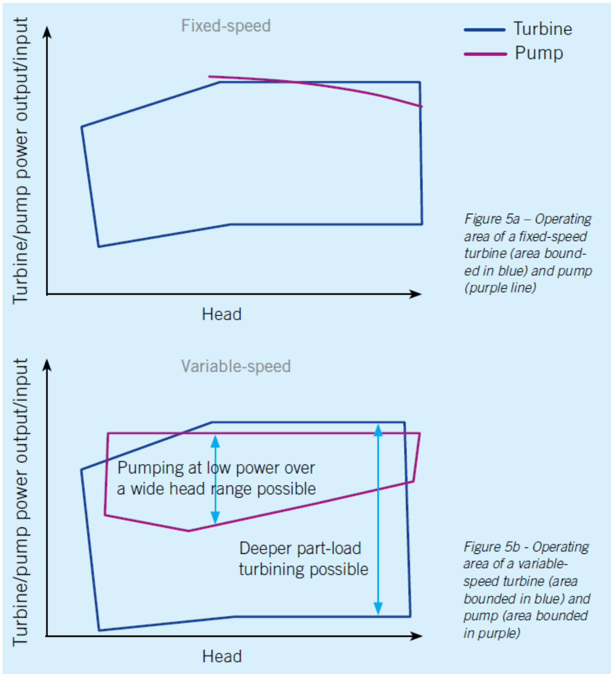


Figure 6-4 Comparison of operating area of variable speed and fixed speed turbines

Variable speed operations also benefit the overall efficiency of the hydropower plant. More specifically, they improve the hydraulic performance. Since at fixed speed, hydraulic machines are optimized for a single operating point, only small deviations in the head and discharge are allowed as higher deviations can lead to reduced efficiency and increased vibration and cavitation problems. In contrast, by adjusting the rotational speed it is possible to achieve an acceptable high efficiency for both large head and discharge variation, and hence the operating range can be extended. These benefits strongly depend upon the plant's operational conditions and hydrology and are more evident where large head variations and partial-load operation can occur. Moreover, the gain in efficiency is particularly significant in the case of reversible pump-turbines. Since turbine and pumping mode have different optimal speeds, at fixed speed operation hydraulic machines can be optimized only for one mode (usually they are optimized for pump mode and then work with reduced efficiency in the turbine mode). On the contrary, with variable speed operation optimal rotational speed and maximum efficiency can be achieved in both modes. Finally, operating pumped-storage plants at variable speeds does not require frequency converters for pumping start-up and synchronization.

The main design solutions available to implement variable speed operations comprise doubly fed induction machines (DFIMs) and converter fed synchronous machine (CFSM).

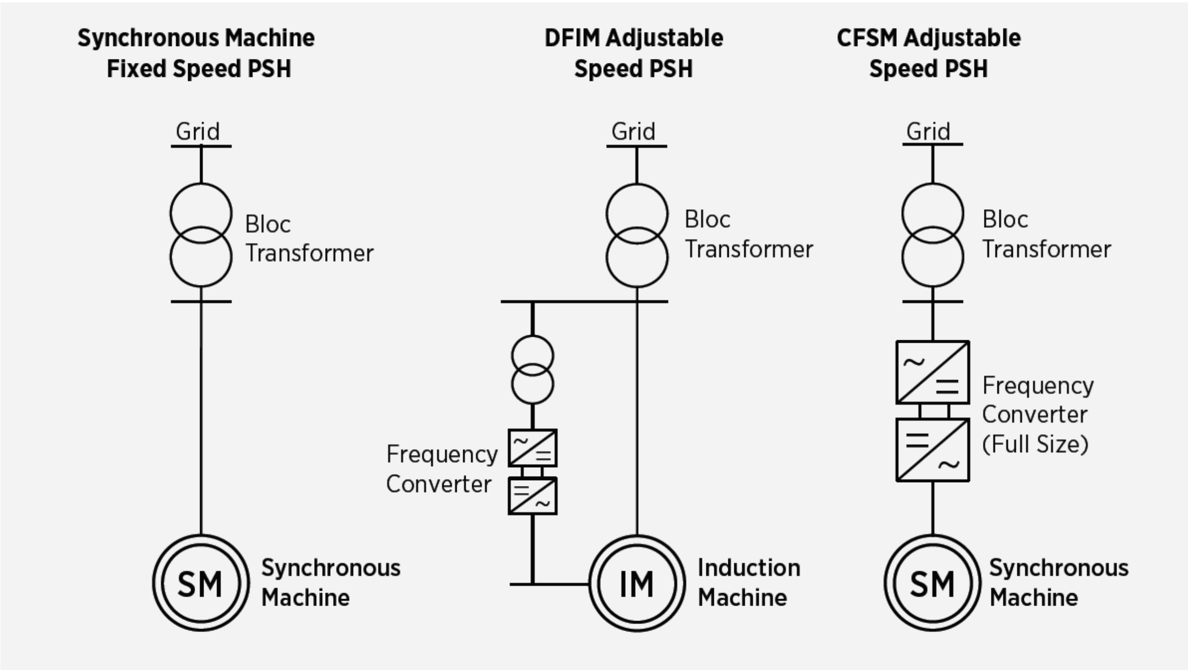


Figure 6-5 Convertor solutions for variable speed operations (Koritarov et al., 2015)

In the DFIM the stator is directly connected to the grid, while the rotor windings are connected via a power electronic converter using slip rings. Through frequency control of the rotor current, it is possible to have variable-speed operation while the stator frequency and voltage remain constant. In CFSM a synchronous machine is connected to the grid via a full-rated converter: a back-to-back VSC is used to connect two ac sides using a dc link. Therefore, the frequency of the motor–generator can vary from the grid. Overall, the CFSM provides better performance than the DFIM. CFSM systems offer easier and faster start-up and do not have limitations on maximum speed (DFIM have speed limits in the range of +-10% the synchronous speed). Moreover, when not connected to the machine, the converter can be used as a reactive current static compensator to supply reactive power to the grid. However, the CFSM needs a full-rated converter, which could be very expensive and not practical for the high-power ratings. Moreover, CFSM can experience higher converter losses than DFIM systems. These drawbacks limit the application of CFSM to hydropower plants up to 100 MW. In short, the CFSM provides superior performance, but the need for a full rated converter is a major drawback. This makes the DFIM more attractive in high-power applications because the converter itself can be considerably smaller.

To conclude, it should be noted that the application of variable-speed hydropower technology is not limited to pumped-storage plants. In fact, it can be advantageous to also employ variable-speed technology in HVdc-connected hydropower plant since in this situation the frequency of the generator is not tied to the grid and the rotational speed can be adapted to optimize operation of the plant. Moreover, small hydropower plants with considerable head and flow variations can also benefit from variable speed operations where variable speed technologies can be used to replace rather mechanically complex turbines with simpler ones, whilst also maintaining high efficiency levels.

7 Efficient and resilient design

7.1 Causes of inefficiencies

The potential for electricity production in a hydropower plant depends upon the hydrology, topography and design of the power plant. Several parameters help determine the efficiency of the power plant:

- the amount of water available;
- water loss due to a flood spill, bypass requirements or leakage;
- the difference in head between upstream intake and downstream outlet;
- hydraulic losses in water transport due to friction and velocity changes;
- the efficiency in energy conversion of electromechanical equipment.

The energy transformation process in modern hydropower plants is highly efficient and usually well over 90% for mechanical efficiency in turbines and over 99% in the generator. The loss of efficiency is due to:

- hydraulic losses in the water circuit (intake, tunnel, penstock, turbine and tailrace);
- mechanical losses in the turbo-generator group;
- electrical losses in the generator, transformer and power ducts.

The sum of these three losses determines the total efficiency of the power plant. Head losses can be reduced by increasing the area of the headrace and tailrace tunnels, by decreasing the roughness in these tunnels and by avoiding too many changes in flow velocity and direction.

In addition, the efficiency of plants depends to a great extent upon the reliability and availability of the equipment, which can be affected by aging, wear and tear, sudden outages, etc. These issues are addressed in detail in Chapters 8 and 9.

7.2 Modelling techniques

The efficiency of electromechanical equipment, especially turbines, can be improved by better design and by also selecting a turbine type with an efficiency profile that is best suited to the duration curve of the inflow. It is therefore important to accurately model turbulent flow and system performance for a wide range of discharge rates. Computer tools are used to find designs that avoid vortices and related pressure pulsations and cavitation caused by the movement of water through the turbine. They are also used for optimising the interaction of the electromagnetic field of the generator's rotor with the stator and to predict the build-up of heat in generators and subsequently the flow of cooling air or water needed to keep temperatures down.

The main design tools used by the hydropower industry are laboratory reduced-scale physical models and computational models. Hydraulic models (both laboratory and numerical) are generally used to simulate conditions for environmental enhancement, dam operation and turbine design and optimization. The sharp increase in computational power in recent years has led to significant use in the hydropower industry of computational fluid dynamics (CFD) models, which use numerical methods to represent the physics of fluid in motion in the complex water systems of a hydropower facility.

7.3 Advanced materials

The flexible use of hydropower can cause some problems for electromechanical equipment as many hydro plants have not been designed to provide balancing power continuously. The biggest challenges are:

- frequent start and stops (20 or more per day for pumped hydro in contrast to 3 per day formerly), and the mechanical and temperature-related stress that they put on the stator winding insulation;
- fast response, meaning adjustment of operating point several times per minute and the associated wear and load on the regulating mechanisms;
- voltage peaks due to the frequency converter, and their effect on the generator winding insulation.

On top of that, cavitation, draft tube pressure pulsations and vibrations are also more likely under these conditions, thus damaging electromechanical equipment. Moreover, high concentrations of hard particles in the water, especially hard and angular ones such as quartz and feldspar, can harm certain turbine parts, quickly abrading surfaces and causing the turbines to become less efficient. Surfaces exposed to a high relative water velocity are damaged the most. For Francis turbines, the eroded parts are mainly the guide vanes, facing plates, labyrinths and runners; for Pelton turbines, they are the runners and injectors. These parts may need to be treated almost as a consumable and overhauled or even replaced after each flood season.

In reservoirs, sediments may have time to settle, but in run-of-the-river projects most of the sediments may follow the water flow to the turbines. The traditional solution to the problem has been to build de-silting chambers to trap the silt and then to flush it out into bypass outlets, but it is very difficult to trap all particles, and especially the fine ones. New solutions are being developed by coating steel surfaces with a very hard ceramic coating, protecting against erosive wear or at least delaying the process.

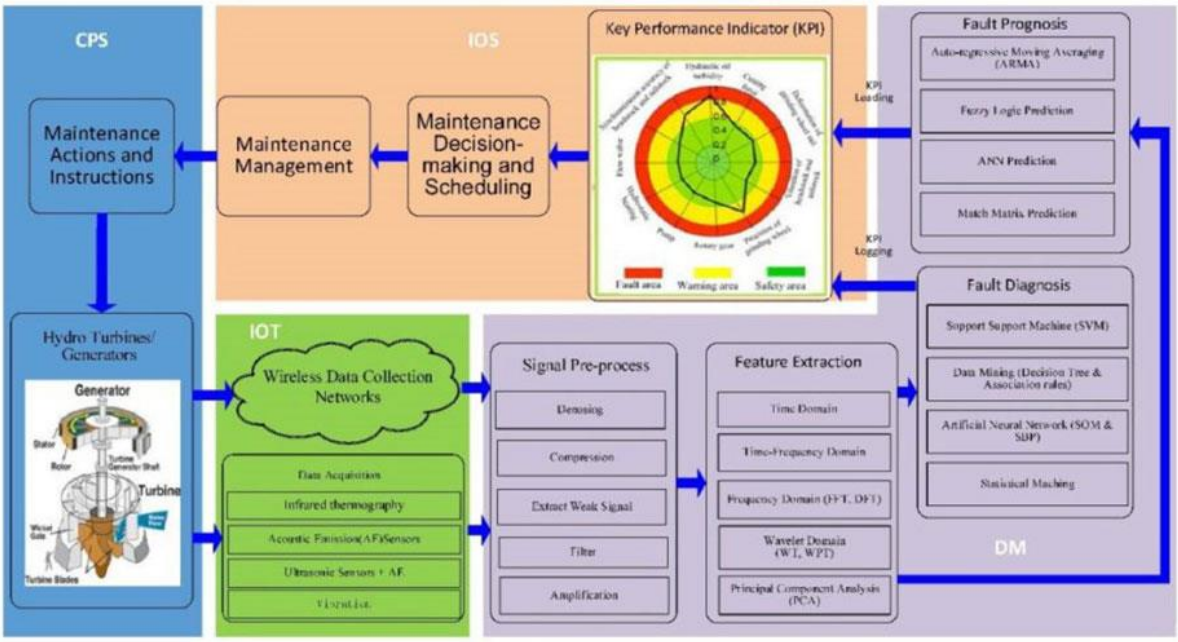
There are high direct costs associated with repairing and replacing cavitation damaged turbine blades. However, materials science applications such as Cold Spray, may reduce the cost of deploying new hydropower or extend the lifespan of existing hydropower projects. Cold spray is a method that works by shooting metal particles at very high speeds into the damaged area; the impact energy created by these high speeds produces a solid- state weld between the particle and the turbine surface. With this technique, melting and material degradation common in current welding repair techniques does not occur and hydropower turbine blades are left in their original shape. Cold spray repair is capable of depositing materials with hardness and wear resistance that match or exceed that of the turbine base metal. An alternative is to use friction stir processing. Similar to cold spray, friction stir processing creates novel compounds that can be stronger and longer lasting than the base metal, giving components new life or making new components cheaper by only requiring high performance materials at stress and wear points.

A more effective solution is to use protective coatings. These increase the time between overhaul by a factor of between two and five and reduce the damage to some specific turbine parts by an even greater amount. Longer periods of operation imply higher generation, helping investments to be paid off more quickly by minimizing damage from hydro-abrasive erosion . Therefore, precautions against hydro-abrasive erosion should ideally be taken at the time the plant is designed. Improvements in material development have been developed for almost every plant component.

8 Digitalization in hydropower

Digital transformation is an ongoing process in nearly all areas of modern life. Regarding the generation of electricity from hydropower, established business models and processes are substantially changing due to new components, concepts, methods and models such as "Hydropower 4.0", machine learning, cyber-physical systems, artificial intelligence, internet of things, data mining and internet of services. Digitalization will also affect the maintenance and operation of hydropower plants thanks to the potential for reducing costs and increasing the effectiveness of workforce management. However, as digital technologies are changing rapidly there are many challenges which make the implementation of digital processes in hydropower plants a challenging task.

Networked platform solutions in hydroelectric power plants have to combine previously isolated data and information systems. Data across all areas should be available locally and centrally at the push of a button and enable rapid analyses. Innovative digital hydropower measures include asset management performance, cybersecurity, plant and fleet enhancements and outage management as well as condition monitoring equipment. All of these innovations have the goal of helping operators to build, operate and maintain hydroelectric plant at lower costs. Controlling expenses and energy production, creating a more efficient hydro turbine and building upon automation and data-driven maintenance, take hydropower services to unprecedented levels. Together, these innovations are providing hydropower asset owners with actionable insight from data, in order to increase



the performance of hydropower assets.

Figure 8-1 Concepts of digitalization in hydropower (Wang, 2016)

Figure 8-1 illustrates how different concepts such as cyber-physical systems (CPS), the Internet of Things (IoT), data mining (DM) and the Internet of Services (IoS) can be placed into a predictive maintenance framework that utilizes measured data.

8.1 Asset performance management

As part of the overall maintenance of existing assets, new analytics have been developed; these analytics can optimize unit maintenance to reduce O&M costs through reduced outage time, while the life of the asset is extended. Asset management is becoming increasingly challenging across the sector as a growing number of hydropower assets need to be refurbished. Asset managers use digitalization to craft and implement strategies for greater value and reliability from existing hydropower assets. Digitalization will help to ensure that the role of hydropower as a flexible, renewable energy resource is optimized within the context of planning and operation of both existing and future energy systems. Currently, digitalization has already been deployed in the modernization of existing hydropower assets, in order to improve overall unit efficiency through upgrades to turbines, draft tubes and other associated equipment. Nevertheless, exploiting the full potential of digitalization in this area at present is challenging since relevant data are often ubiquitous, compartmentalized, incomplete, of insufficient frequency, of unknown quality, misaligned in time, and altogether inadequate for pattern recognition and cause and effect determination.

8.2 Condition monitoring equipment

Hydropower, as one of the largest and most efficient renewable energy sources, contributes to grid stability due to its scale of production and flexibility. Adaptability is another important feature that makes hydropower a key technology for integrating other intermittent renewable sources of energy into the grid. In this context, hydro utility companies are changing the way that they operate their plants, switching from baseload to more flexible power production. Therefore, intelligent condition monitoring and diagnostics become crucial. To adapt to this changing production mode, hydropower plant operators are looking at expanding the time between plant overhauls (TBO) and shortening the mean time for repair (TTM). Intelligent monitoring systems allow managers to track the health of the plant and to detect failures before they happen, so that the plants can be repaired at the best possible time to minimize downtime. Internet-enabled Condition Monitoring Systems (CMS) remotely collect and analyse real-time data, in order to improve diagnostics and prognostics on faults in the plant.

8.3 Outage management

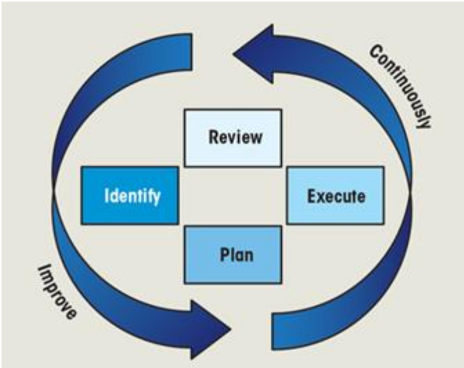


Figure 8-2 Continuous improvement cycle

The moment a hydropower plant or unit comes out of service due to an outage, it stops generating revenue. The economic impact of poorly planned and executed outages can be severe.

The loss of availability or capacity due to outage extensions or later reworks dramatically impacts the annual return. To effectively prepare for and execute an outage - and rein in on unexpected costs and schedule slippage – it is necessary to defined outage management processes based on four pillars: Identify, Plan, Execute, Review (Figure 8-2).

To properly manage an upcoming outage – and to lay the groundwork for improving the next one – it is important to identify the activities that require attention and the metrics for assessing (after the outage) how effectively they have been implemented. Successful maintenance management identifies the outage work list from various sources, including:

- work requests resulting from the post-outage critique meetings and capturing tasks identified during the previous outage;
- regulatory issues, which impose additional tasks and, in some cases, determine the frequency of outages;
- outage and equipment history, which should be used as another major source for identifying outage work items;
- Preventive maintenance activities, backlog or carryover work from previous outages.

Successful outage planning requires that important events occur far in advance. The list of identified works should be locked down in time. Otherwise, a flood of add-on work items can appear and lead to reactive responses, excessive costs and schedule overruns. If add-on work is unavoidable, the requestor should be asked to justify the need for it and to identify existing work items that can be sacrificed to compensate for it. However, this situation should be avoided, since it is wasteful to cancel a job that has already been planned (with parts on order or already delivered) in order to undertake unplanned work.

Execution is also a question of scheduling. Scheduling involves knowing how much work is available, how long each task will take, how much labour resource is required per task and how tasks need to be prioritized. A successful schedule also has to be conversant with day-to-day execution. Daily schedule updates are essential. Without them, completion of the outage on-time can be jeopardized.

Measuring the right things, in the right way and at the right time, as well as communicating them appropriately, allows control of activities whilst work is being executed. Poor documentation is usually at the root of cost and time overruns, but if problems continue in the future, it's often because the right systems have not been in place to identify the problems.

8.4 SCADA hydropower

Many hydroelectric power plants are in a process of rehabilitation and upgrade, in order to ensure optimized operation. One way to optimise power production plant is to remotely control all power production units through a Supervisory Control and Data Acquisition (SCADA) system. This type of system handles both software and hardware techniques based on Personal Computer (PC) resources, Powerline Communications (PLC), Remote Terminal Units (RTUs), smart sensors and data communication and transfer devices. SCADA system requirements are:

- up and down openness;
- adaptability;
- real time operating;
- data security and reliability;
- user friendly interface;
- availability and correctness (accuracy);
- self-test capability.

8.5 Internet of Things (IoT) in hydropower

The Internet of Things (IoT) and Big Data-analytics have revolutionized the future of the energy sector. Along with a solid digital infrastructure, IoT enable access to data almost anywhere in the world; it also allows analysis of data, thus mitigating the risk of investments in energy assets and helping to maximize the portfolio performance. This type of analytics is the driving force behind standardized management of energy assets around the globe. This makes it possible to produce power, monitor performance and manage portfolios efficiently within large networks.

The use of remote sensors increases in parallel to the uptake of IoT. Sensors can provide a continuous, high-rate stream of data to keep operational staff informed on everything (from overall stability to the heat-generation within turbine bearings). Sensors are relatively simple to source and install. The challenge lies in finding the skills capable of envisaging and implementing data-driven operations. Installing and managing an operating environment made up of thousands of sensors is a complex issue. Equally complex is to establish how theoretical connections between diverse sensor groups can be turned into direct operational advantage. The range of industry-specific and IT skills needed here is quite wide. Expertise in developing the cognitive machine-to-machine communications is needed to tune hydropower performance according to demand and environmental conditions. At the same time, skills to integrate operational and information technologies are needed.

Preparing accurate forecasts and linking these to trading systems, for example, combines expertise which has traditionally been separated according to professional focus.

For many years, utilities have been applying data analysis to forecasting for generation and consumption and for optimized trading. However, significant changes have occurred in both the operational models affecting hydropower and in the ways in which analytics, cognitive computing and the Internet-of-Things can be used to create operational advantage. In this new landscape, open data becomes particularly important.

An energy mix can only work if it is data driven. This is not just about managing the power grid but is also about being able to create operational models with multiple and multi-scale providers. Collaboration between entities that would once have seen each other as competitors will become the norm. Cognitive computing has a real impact too, as the outputs of continuous analytics become the inputs for active machine learning. Across the wider ecosystem, cognitive computing can aid hydropower operators to increase the efficiency of collective planning and production both with major grid suppliers and with smaller independent producers.

These new levels of mutually profitable collaboration can draw on the wider sources of open data and on their looser operational associations. Hydropower operators, for example, can now make both real time and historic consumption forecasts part of routine next-day planning. To do this, they can draw on sources as diverse as the open data of meteorological experts and the production forecasts of local industry.

8.6 Artificial intelligence and machine learning

Ageing plants can be expensive to run, but costs can be saved in maintenance through better planning and targeted maintenance enabled through digitalization. In recent years, digitalization in hydropower has moved to the next phase, which involves the development and testing of a variety of algorithms and methods designed to analyse operational data from power plant control systems. Models and algorithms using operational data from control systems, as well as from other sensors and measuring equipment installed within the plants, have been developed. These systems, also known as “digital twins”, provide prompt notifications of changes in function or performance.

Models and algorithms will increasingly help companies to identify faults or, more precisely, future faults in the plants. The aim is to identify such faults before a serious malfunction occurs. Through digitalization and suitable concepts, the hydropower industry has great potential to rationalize maintenance processes and cut costs.

9 Operations and maintenance

9.1 Operations planning

Hydropower facility owners need to operate under various constraints, including maintaining environmental quality, preventing flood risk, and providing adequate municipal water supply whilst also supporting recreational activities. In order to optimize the use of available water, operations are carefully planned. Generation is estimated based on projected rainfall/runoff forecasts (snowpack levels are used in mountainous and northern climates). Safety and operability are largely improved by weather forecasting programs informing the operator of rainfall amounts and water volumes that should arrive at the power plant several hours to several days in advance. This dynamic planning process requires revision over time. Unit outages, which are executed during periods of low water availability, are also planned in this process using availability calculations such as equivalent availability factor, equivalent forced outage factor and facility electrical capacity.

9.2 Automation and digitalisation

Hydropower plants are usually highly automated as they are typically in difficult to access areas. Many hydropower plants are unmanned, relying on regular service cycles and automation systems to discover any anomalies that could lead to dangerous events. Plants are controlled or operated remotely as a power plant pool and software algorithms automatically control many processes. SCADA systems supervise, control, optimize and manage generation and transmission systems. The main components of these systems are Remote Terminal Units (RTUs) that collect data automatically and are connected directly to sensors, meters, loggers or process equipment. They are located near the monitored process and they transfer data to the controller unit when requested. They often include integral software, data logging capabilities, a real-time clock and a battery backup. These devices are complete remote terminal units that contain all of the transceivers, encoders, and processors needed for proper functioning in the event that a primary RTU stops working. Meter readings and equipment status reports can also be performed by Programmable Logic Controllers (PLCs).

Digitalization is a key enabler for more streamlined and efficient processes, remote possibilities, better networks and sophisticated communication channels. Workforce management applications are already a certainty in many hydropower plants. At the same time, digitalization is increasingly used in preventive and predictive maintenance as it allows the processing of huge amounts of data to provide better analyses of risk; in fact, it allows the detection of anomalies in a more cost-efficient way and provides the intelligence to support more accurate judgements.

9.3 Maintenance strategies

Next to efficiency, the availability of a power plant determines its productivity. Minimising outage time and optimising maintenance intervals is a considerable challenge for all hydro plant managers, especially those delivering balancing power because of the related dynamic operation, dynamic loads and increased wear and tear. Maintenance programs are intended to reduce or eliminate unplanned equipment failures, so disruption in electricity generation is avoided. These programs foresee routine maintenance of the facility, equipment for water conveyance (e.g. spillway gates, water conduits, flumes), hydraulic equipment related to the turbine and the generator, switchgear, balance of plant and the step-up transformer. Maintenance strategies are usually designed taking into consideration reliability, production costs, outage times, maintenance costs, and other strategic criterion. Overall, it is possible to distinguish different types of maintenance as follows (DOE, 2016):

- **condition-based maintenance** consists of scheduling inspection and maintenance activities only if problems are detected by periodically monitoring the machinery or by observing abnormal trends that occur over time. To this purpose equipment is often provided with sensors that can detect changes in equipment performance and monitor anomalies that may require corrective maintenance.
- **time-based preventative maintenance** is based on inspections performed on a schedule based on calendar time or machine run time. It is not intended to solve a specific problem, but rather to detect and mitigate degradation of a component or system and to extend its useful life. This is the most common maintenance method in hydropower facilities. Time periods for maintenance activities are usually determined based on operating experience, manufacturer recommendations, or regulatory requirements. Most maintenance activities are carried out during planned outages, which allow facility owners to conduct inspections, repair, cleaning activities and diagnostic tests. These include maintenance of waterways, turbines, generators and transformers.
- **Corrective maintenance** is not planned and is applied when equipment ceases to function. This approach does not require monitoring systems, but it can cause downtime, major drawbacks and generation and economic losses when failures appear. Therefore, corrective maintenance in a hydropower facility is generally limited to components that are not mission-critical or that can be replaced within a few hours.
- **reliability-centred maintenance** is a systematic approach based on the combination of predictive and preventative maintenance techniques to achieve the highest degree of facility reliability and cost-effectiveness. It implies gathering O&M data, performing analysis and developing options for maintenance. Following a first round of maintenance, feedback is gathered to see if the options were optimal and accurate and adjustments are made as needed. This process is then repeated on a regular basis.

Whilst traditional approaches are mainly built on preventive and corrective maintenance, predictive maintenance can bring considerable benefits to hydropower plant operations. In fact, with a real-time monitoring system analysing the health of the plant components, action can be taken in a timely matter, extending operation and giving better planning for scheduled maintenance. While preventive maintenance implies constantly monitoring the status of a power plant and the proper operation of its components (thus requiring significant time and resources), predictive maintenance represents instead a significant change of pace thanks to its data-based management strategy. Predictive maintenance requires a significant number of sensors that gather an enormous set of data from all components. These datasets are analysed through specific models and advanced algorithms to provide detailed information on equipment and infrastructures, thus allowing maintenance teams to schedule works before a potential fault could happen and optimizing costs and man-hours. More specifically, integrated decision support tools for asset lifetime management utilize real-time data for monitoring the condition of critical FCRPS assets and enable calculation of remaining service life estimates (along with confidence bounds) for monitored assets. They also perform integrated risk analyses to predict changes in operational risk based on the monitored condition of assets and enable cost-benefit assessments for predictive maintenance scheduling. Finally, they provide potential inputs into operational decision making for plant control, by enabling what-if assessments that incorporate real-time component condition and predictive failure probabilities.

9.4 Remote monitoring hydropower plants

In order to ensure the safety of hydropower structures and the efficiency of electromechanical equipment, a large number of monitoring instruments need to be installed for measuring critical parameters. These instruments can be embedded into the structure itself, during construction, or installed into the surrounding area and facilities. A large hydropower structure could have hundreds of monitoring instruments installed. Most of them are equipped with electrical sensors so that they can be remotely monitored. The most common types of sensors used by hydropower monitoring instruments are:

- vibrating wire sensors;
- resistive sensors;
- current or voltage output industrial sensors;
- inductive, frequency output sensors;
- serial digital output sensors.

The complexity of dams calls for the use of multiple sensors for monitoring. Each sensor focuses on a different area of the main barrage, the slopes surrounding the reservoir and the utility structures. Measurements are usually made at a specific number of control points, properly established in key locations to allow extrapolation of the behaviour of the whole structure.

Dam monitoring has benefited from the development of remote-sensing techniques from ground-based and satellite platforms. Among these techniques for areal deformation measurement two types of ground-based sensors are included: terrestrial laser scanning and ground-based synthetic aperture radar (SAR).

As for the electromechanical equipment, the vibration signal is the most commonly used indicator for evaluating the health status and stability of the hydropower generation unit, since vibration tendency prediction is essential in ensuring safe operation and conducting condition maintenance. However, other types of sensors are also commercially available. Acoustic monitoring systems allow the supervision of large spaces with many machines and systems simultaneously providing additional added value to facility operators compared to traditional conditional monitoring systems, which rely on sensors mounted on dedicated machine parts. Equipped with a sound recorder for acquisition, pre-processing and transmission of sound data, and a data recorder for acquisition, pre-processing and transmission of process data, these systems allow the operator to easily detect anomalies based on frequency spectra and to decide if they need to take action.

9.5 River forecasting and water use optimization

Hydropower operators release water in a way that optimizes power generation whilst balancing economic, social, and environmental objectives. Several analytical tools have been developed to support operators in planning and scheduling on a spatial and temporal basis. Real time river system modelling tools have been developed for operational decision making, responsive forecasting, flood management and emergency action planning, system optimization and long-term resource planning. These real-time modelling tools allow the user to compare several planning alternatives by modelling hydrologic and hydraulic processes, hydropower production, and water quality parameters such as dissolved oxygen, total dissolved gas, and temperature amongst other factors. Hydrodynamic and water quality and optimization models are capable of simulating and predicting how watershed management practices might affect the water quality of a reservoir. These models use several assumptions and approximations to simulate hydrodynamics and transport to predict variables such as water surface elevations, velocities, temperatures, and a number of other water quality constituents.

10 Infrastructure resilience

Resilience refers to the ability to return quickly to a previous good condition after problems arise. In hydropower structures it also means the capacity and adaptability to operate in adverse situations, which may be extreme or slightly different from those for which the power plant and related infrastructures were designed. Extreme adverse situations for hydropower plants and infrastructure security derive mainly from floods and earthquakes. The priority is therefore to increase the resilience of infrastructure against these threats. Another source of risk is the ageing of infrastructure. In the coming decades, more and more infrastructure are going to reach the end of their expected life span (100 years) and most of them will need some form of retrofit. Through regular risk assessments, infrastructure owners can keep risks from natural events under control. Ageing related risks are better addressed through predictive maintenance, which can allow for an increase in infrastructure lifespan. This involves improving surveillance systems to detect the early stages of ageing, developing behavioural models to predict the evolution of ageing, setting repair criteria and testing reinforcement techniques.

10.1 Flood resilience

Flood control in hydropower infrastructure has been largely improved in the past decades. Flood management simulators have raised the level of awareness and the experience of staff operating hydropower plants. Methods for flood estimation have been largely improved by analysis of large datasets and the inclusion of new weather (loading) patterns. The loading cases have been clarified and refined. Two major events are considered: the **design flood** and the **check flood**. The return periods of both events have been (typically) increased, based on risk assessments. The increase of return period leads to an increase of capacity discharge and the need for the recalibration of spillways: piano key weirs and concrete or metal fuse gates are often the main solutions for spillway recalibration. With flood routing changed and improved, innovation has led to new solutions to prevent overtopping, including the use of concrete slabs, shotcrete spillways embedded into the embankment and secondary spillways in RCC placed on the downstream face of embankments. Consideration of climate change effects has been included in the most recent hydrological studies. Shared views on climate change trends are necessary to strengthen assumptions and conclusions and verification of the consistency of guidelines adopted in European countries is one of the most important current steps to improve the security of hydropower in Europe.

The rationale to improve flood control by hydropower infrastructure lays in the need to:

- ensure the downstream population are protected from flood effects;
- increase the level of awareness of dam owners and public authorities;
- accommodate climate changes effects; and

- ensure compliance with national and European legislation.

The main impacts for the industry of doing so are the:

- increasing exploitation of reservoir flexibility; and
- need to maximize energy production under changing conditions

10.2 Earthquake resilience

Earthquake resilience is also a priority to ensure infrastructure safety. ICOLD Bulletin 148 (2016) updated existing guidelines for seismic safety, introducing new and more embracing concepts. The loading cases have been confirmed and refined. Two major events are considered: the operating basic earthquake (OBE) and the safety evaluation earthquake (SEE). The return periods of both events have been clarified and increase with risk. The guidance includes seismic design criteria to be applied to dams, to the appurtenant structures and to relevant electromechanical components (bottom outlets, spillway gates and power units). Relevant new geophysical methods based on ambient noise recording and processing can capture the fundamental period of vibrations of the structure. Sophisticated dynamic analysis methods, which allow for calculation of the nonlinear seismic response of embankment and concrete dams, are available; however, their results should be verified with observed data. Most existing dams were designed using old methods and it is highly advisable to re-evaluate their seismic safety. Many small dams are very sensitive to earthquakes and reinforcement works may be necessary. Multiple seismic hazards associated to rockfalls, landslides, ground settlements, liquefaction and other factors, should also be considered.

Dams of various types have already been subjected to intense, high magnitude ($M \geq 6$) earthquakes with epicentres at relatively short distances from the dam site. There are several publications reporting their effects; it would be very useful to collate such feedback in a unique European data base and extract best practice from it to help limit future damage caused by earthquakes.

10.3 Risk assessment and civil society protection

The current **risk analysis framework** is a mature approach, which is increasingly applied across different countries. For example, risk analysis is used as the primary support for dam safety decision-making for the U.S. Bureau of Reclamation (Reclamation) and the U.S. Army Corps of Engineers (USACE). Ad-hoc methodologies and guidelines have already been produced for the dam safety problem, and the topic is often included in conferences in the sector. It has showed its suitability for prioritising investment in dam safety and governance, since it facilitates the identification of risk contributors and objectively quantifies the impact and efficiency of potential risk reduction measures. There is also a tendency to move from deterministic to probabilistic methods. This allows engineers to balance engineering judgement and calculations in all aspects of dam safety. Furthermore, different levels of risk analysis have been developed, from screening level assessments by a few individuals to a significant, in-depth team risk analysis such as with the Oroville Dam spillway incident in California, USA. In this context, numerical models are invaluable estimation tools for failure probabilities associated with a given failure mode via reliability techniques. For example, the uncertainties in the inputs of a model are propagated towards its result, so that a density function can be obtained instead of a deterministic value. This kind of analysis typically requires a high amount of cases to be executed requiring significant computational time, which is often not feasible. Thus, they may be limited to the use of relatively simple numerical models or even to analytical expressions.

Hydropower plants are key **critical infrastructures**, as other facilities depend upon their provision of energy for their daily operations. It is therefore heavily regulated and much of the information surrounding security issues is confidential. This situation makes it very difficult for energy utilities to openly share information about security solutions and share their resources for research and innovation. Due to the very nature of the current infrastructure of the energy sector, and the ramifications of security failures, the energy sector has some of the most secure and protected critical infrastructure in Europe. Security is considered from the very outset (security by design) for all energy producing plants and networks, as they are vulnerable to both man-made (terror or error) and natural disasters.

Recently, **cyber threats** have become a serious concern in the energy industry. These can often have repercussions in the physical domain. This is of major concern, as in many countries the regulatory agencies dealing with physical threats are separated from those dealing with cyber threats; moreover, often little or no collaboration is in place. A coordinated approach involving all relevant stakeholders is needed.

10.4 Increase in lifetime of infrastructure

The main elements of hydropower projects include dams, spillways, bottom outlets, hydraulic circuits, intake and outlet structures and powerhouses. The performance of this infrastructure strongly influences not only the reliability of operation but also the safety of the hydropower scheme. Detected anomalies, incidents and/or accidents are indicators of unsatisfactory performance and the need for improvements. Investments for infrastructure rehabilitation are mainly related to:

- recalibration of design floods and spillway capacity;
- improvement of the seismic resilience of dams;
- addressing swelling of concrete dams;
- improvement to erosion resistance of embankment dams;
- improvement of dam surveillance.

10.4.1 Ageing of concrete: concrete expansion of dams

Concrete swelling phenomena, associated in particular with Alkali-Aggregate reaction, represents the major worldwide problem affecting concrete dams and structures of hydropower projects. For instance, the ratios of affected dams are 32% of dams (19 in 60) in Portugal; 20% (31 in 156) in France; 14% (22 in 154 dams) in Switzerland. Other cases worldwide are disclosed in specific bibliography. The issue is so huge that decommissioning or replacement has already occurred (e.g., replacement of the Sera Dam in Switzerland and the Alto Ceira Dam in Portugal). Most usual expansion reactions are Alkali-Aggregate Reactions (AAR), including alkali-silica reactions (ASR), Internal Sulphate Attack (ISA) and Delayed Ettringite Formation (DEF). They can occur at any concrete age (from 0 to 50-80 years). Their main effects are severe cracking and mechanical degradation properties, irreversible displacements, movements causing interference with spillways gates and other equipment, and a decrease of structural safety. Expansion process management includes several mitigation measures attempting to control the rate and the duration of the phenomenon (PVC géomembrane to prevent water from entering the concrete), anchors (post-tensioned high tensile or unstressed mild steel anchors to secure the cracked concrete areas), grouting (cementitious and/or epoxy slurries), concrete slot cuts, application of epoxy coatings, gate and equipment adjustments and implementation of dedicated monitoring systems. The objective is to extend the useful service life of the structure by monitoring its security and performing structural assessments using numerical models.

10.4.2 Dam surveillance

ICOLD issued a set of Bulletins with important guidelines concerning dam safety (namely, 118 - 2000, 138 - 2009, 158 - 2013), underlining the role of surveillance to prevent progression of failure mechanisms. Surveillance aims to reduce the probability of incidents occurring and of dam failure, by allowing analysis of the dam behaviour, identification of potential failure modes, early detection and estimation of the associated risk levels, and implementation of Emergency Action Plans.

Government Agencies have issued legislation to enforce and control effective dam surveillance. The operator has the main responsibility for all aspects of dam safety, including reducing the consequences of any dam failure. Hydropower operators generally use the best and updated practices on dam monitoring. However, for existing dams, instrumentation systems can be outdated or not reliable, and re-instrumentation can be necessary. The risk level of the dam, the criticality of the information provided and the cost and the installation opportunity are all issues to be considered to improve monitoring systems. Extensive new developments in dam instrumentation have emerged more recently and can be applied to existing dams with relatively limited installation work.

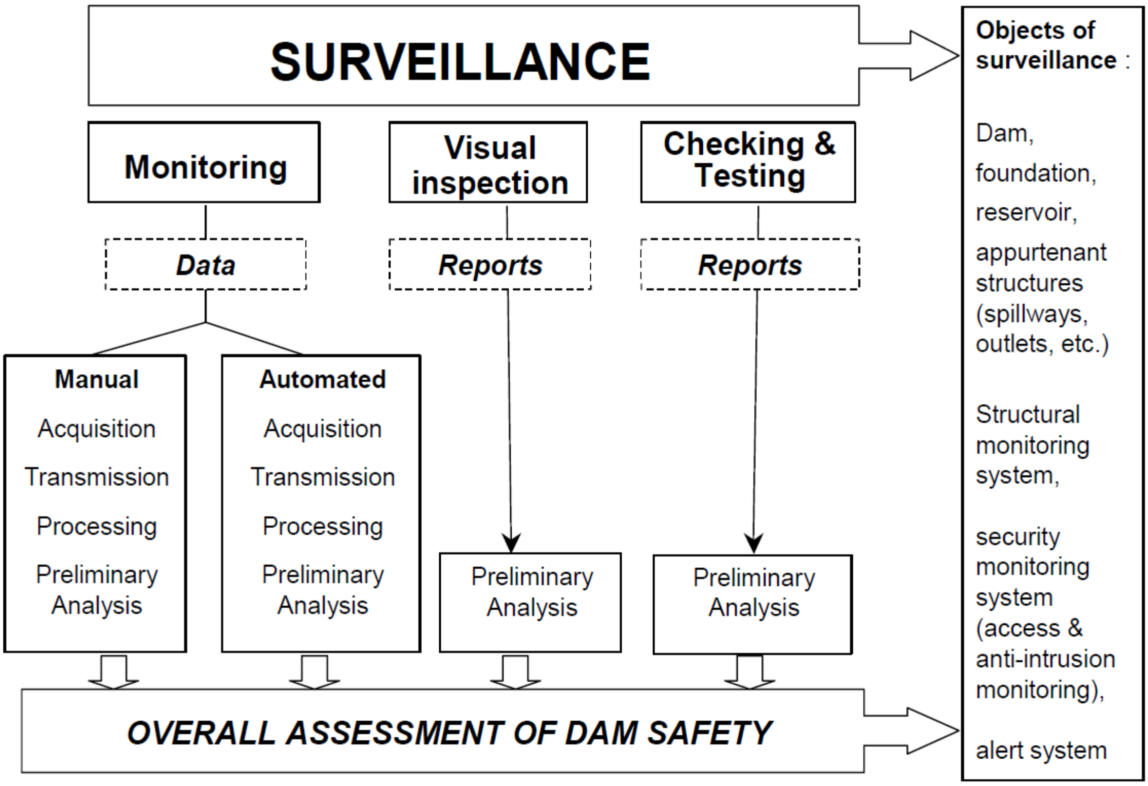


Figure 10-1 Conceptulisation of dam surveillance systems

Alongside the installation of sensors in equipment and infrastructure, methods for remote sensing also exist:

- satellite images based on InSar techniques are used to monitor creep or slow slippage of the river banks;
- drones (UAV) are more and more used to do local topography surveys by photogrammetry or to measure flow velocities;
- sonic cameras embedded in boats or robots make it possible to obtain precise bathymetries during underwater dam inspections; they can detect the occurrence of sinkholes, cracks or holes in dams or in their foundations;
- new cheap thermal cameras are used during visual inspection for detecting wet areas and hidden leaks from the ground.

10.4.3 Ageing of earth structures: internal erosion

Internal erosion is a mechanism where seepage causes soil particles to detach and move within the dam body or foundation. Over time, the erosion can cause significant removal of material creating significant and ever larger seepage flow paths and it is responsible for the failure of nearly half of failed hydraulic structures (dams, dikes and canals). Decisive progress has been made in the past decades in the detection and modelling of this phenomenon. For example, fibre optics can be installed at the base of the structures to continuously and remotely monitor for signs of internal erosion (changes in flow rate, temperature and deformations). One of the main challenges for old earthen hydraulic structures is to strengthen and uprate the monitoring system in order to identify and prevent erosion phenomena from being allowed to develop.

10.4.4 Underground structures

The waterproofing of underground structures is an important issue for hydropower operators. Currently, it is provided by expensive steel armour. Concrete galleries have long and expensive reinforcement. Hydraulic fatigue of concrete structures needs to be further explored. The installation of PVC membranes in concrete galleries is an upgrading solution that improves waterproofing and reduces roughness, allowing the operator to make substantial financial gains by increasing flow rate and load.

The hydro-mechanical behaviour of fractured rock masses has not been deeply studied and old rules are still used. Tests and analyses are needed for a better understanding and a better use of the rock. The stability of surge tanks and the safety of pressure shafts under biphasic flows and air entrainment are two relevant issues affected by the future harsher flow conditions imposed by increasing the flexibility of operation.

11 Environmental and social issues

The development of hydropower projects can have both positive and negative environmental and social impacts. Hydroelectric structures can affect the ecology of a river by changing the hydrologic characteristics and disrupting the ecological continuity of sediment transport and fish migration through the construction of physical barriers such as dams, dikes and weirs. From a social impacts perspective, hydropower may require the relocation of some local population, but is also usually a driver for socioeconomic development. Moreover, it may affect land use, the economy, and the health and safety of local communities. Equally, however, local communities may benefit from hydropower projects through not only generating electricity, but by also enabling other water-dependent activities such as irrigation, navigation, tourism, fisheries and provision of water supply to local municipalities and industries while also protecting against floods and droughts.

The main environmental and social issues related to hydropower projects, as well as the magnitude of any effects, are typically site dependent, since each hydropower plant is uniquely designed to fit the site-specific characteristics of a given site and the surrounding society and environment. It should be noted that run-of-river HPPs do not alter the river flow regime, whilst the creation of a reservoir for storage hydropower often entails a major environmental change. In general, hydropower has a significant environmental footprint at local and regional levels but offers advantages at the macroecological level.

From an environmental viewpoint, hydropower projects need to address five main challenges:

1. Ecological continuity (fish migration and sediment transport)
2. Water quality
3. Environmental flow
4. Hydropeaking
5. Mitigation hierarchy for biodiversity

Moreover, although hydropower does not produce greenhouse gas (GHG) emissions during operations, methane (CH_4) emissions from reservoirs might be substantial under certain conditions and this implies the need to properly assess the net change in GHG emissions induced by the creation of such reservoirs.

11.1 Fish migration

As stated above, dams may create obstacles for the movement of migratory fish species, thus reducing access to spawning grounds and rearing zones and eventually decreasing migratory fish populations. The upstream migration needs of fish, especially salmonids and amphihaline European species, are quite well documented (via guidelines, reported feedback etc). However, the downstream migration behaviour of fish is less well known (except for salmonids and eels).

Upstream fish migration can only be facilitated with civil works installed on dams (fish ladders, fish lifts etc.) or with artificial by-pass rivers (when possible, to by-pass small dams). These devices are quite efficient, although they can cause migration delays which may be detrimental for some fish populations.

Downstream fish migration poses more significant challenges. In these cases, minimizing negative impacts on fish populations may be possible by various construction or operational measures. Solutions are designed according to the characteristics of the site and fish species and include:

- **Fish-friendly turbines**: to achieve this, turbine design aims to minimize the gaps between rotating and stationary components, create blunt leading edges on runner blades and reduce runner rotational speed. Also to minimize the number of runner blades and/or allow for low turbulence.
- **Surface or bottom by-passes** for higher dams: in this case screens or other type of fish barriers are placed in front of the water intake to prevent fish from being carried to the turbine and to guide them to the fish pass.
- **Operational measures**: in certain cases, turbine shutdowns or spillway openings may be necessary at certain periods to let the fish (mainly eels) pass through the gates of the dam.

However, for each of these devices, the hydraulic conditions are not always optimal and residual impacts on fish may be important. Fish survival is really site and species dependent. Moreover, the fact that fish-friendly design may increase head loss and maintenance costs needs to be taken into account. Reserving water for fish movement or taking plants offline to allow fish migration, entails a loss of revenue for the plant owner.

When fish are attracted to the plant instead of the fish passage, it may be necessary to install fish barriers on the tailrace. Different types of barrier, such as strobe and laser lights, acoustic cannons, bubbles and electric fields, have been tested or implemented, but their efficiency has not been clearly demonstrated and, again, is highly site and species dependent.

In order to guarantee cost as well as ecological effectiveness, projects and measures need to be assessed site specifically; there might also be cases where facilitating fish migration will not be relevant, such as:

- where fish migration is already prevented due to other (natural) barriers;
- where no suitable habitats can be found or created up or downstream;
- where no water type specific habitats can be realised;
- at dams, where no significant ecological improvements are expected;
- where a separation of species makes sense and is also preferred for environmental reasons, such as the protection of specific populations from disease or displacement;

- in case autochthonous populations exist above the barrier to migration.

11.2 Sedimentation

The sediment load of a river is composed of sediments from the riverbed and sediments generated by erosion within the drainage basin. By reducing flow velocity and the slope of a river, dams can decrease the sediment carrying capacity of a river. Sediment deposited in the reservoir reduce its storage capacity and can lead to the raising of riverbed levels and an increase in flood risk. Additionally, retention of sediments within reservoirs can lead to a deficit of sediments downstream of the scheme with potentially severe consequences (river incision, impact on fish reproduction, etc.).

Sedimentation management techniques aim to lower these risks. For **fine sediments**, mechanical or dredging dilution extraction are current (but expensive) practice. However, the impact on salmonids and other species and therefore the determination of a threshold for sediment management operations, remain very difficult to assess. For **gravels**, reservoir flushing may be undertaken for channels with a high level of coarse transport - but this is not always possible. Where gravel sediments are missing downstream of dams, **restoration of the river morphology** may be implemented to mitigate the riverbed incision and reduce the risks of damage to the river system.

11.3 Water quality

Depending upon the nature of the hydropower plant, substances in contact with the water flowing through the turbines (typically lubricants) can accidentally be released into waterways, thus impacting water quality downstream. Solutions to minimise this risk are available and include oil-free hubs or environmentally acceptable lubricants. However, this kind of pollution remains relatively small compared to the changes in water quality observed with large reservoirs.

The changes in water quality in reservoirs depend upon the residence time of the water, thermal stratification, the sediment quality and the quality of the incoming waters, which depend upon the geological context, land use, nutrients concentrations, climate, etc. Since these factors cannot be managed directly, they have to be assessed in the early phases of project management to design a hydropower scheme that reduce the risk of water quality degradation; the issues to be carefully considered include: site selection, appropriate design, future reservoir morphology and hydraulic characteristics. Hydrodynamic and eutrophication models may be used to help understand how the reservoir water quality may evolve under specific conditions.

The downstream water quality depends upon that of the reservoir and upstream sources. Sometimes the water may be deoxygenated and polluted with organic or mineral pollutants released by the sediment within the reservoir. Therefore, it is important to oxygenate the water again, and different kind of solutions exist depending upon the site.

The emission of greenhouse gases from large, young and deoxygenated reservoirs may also be an issue, even if this is not very frequently found in Europe (in Europe, usually no biomass is left in reservoirs that could lead to CH4 emissions). Once again, the choice of site is essential to limit this type of risk.

Water quality may also be impacted through some dam management operations, such as emptying reservoirs for works. Although short in time, the impact of such operations can be severe and have consequences on aquatic biology or water uses. Many solutions may be implemented to limit the negative effect, including piloting the flushing with water quality thresholds or creating a decanting basin.

11.4 Environmental flows

Sustainable management of environmental flows is a central issue, since it determines both the profitability of a project and its socio-environmental acceptance. Depending on the country, guidelines on this issue may be more or less precise and/or binding. Implementing environmental flows is very often a key measure for restoring and managing river ecosystems. E-flows have to be prescribed and analysed site-specifically. It is crucial how e-flows are defined (daily/monthly/… average flow), as this could make a huge difference to day to day operation and environmental impact.

The objective is to determine the input flow value(s) that enable the maintenance of a well-functioning aquatic ecosystem, and other water uses, whilst allowing for electricity generation. Many methods are available to determine environmental flow for different types of rivers. Most of them are centred on fish community needs, but some holistic methods are available too. Unfortunately, they are not always well adapted to specific environments (e.g., Mediterranean areas or intermittent/large rivers) and they are usually not sufficiently shared with stakeholders.

11.5 Hydropeaking

Hydropeaking may negatively affect the hydro morphology downstream of the plant and aquatic organisms, either directly (mortality by stranding, catastrophic drift, etc.) or indirectly (modification of physical habitats, water quality, etc.). Knowledge of these effects has improved in recent years; intensity, period and frequencies of the peaks and rate of rise or fall of flows are the main factors that can be managed to reduce the negative impacts. Solutions can be provided through both construction (demodulation basin downstream of the plant) and / or operational restrictions. The latter are very expensive and typically not compatible with the goal of flexible production. Moreover, there is still a lack of consensus on the assessment of potential ecological impacts. Therefore, the identification of appropriate mitigation measures that are well accepted by stakeholders is still a challenge, especially when it concerns multi-stressed environments where diagnostics are uncertain.

Hydropeaking diversion power plants entirely prevent flow fluctuations providing an ecologically appropriate residual flow and a suitable location for reintroduction of flow to the river system. From a business perspective, new diversion power plants are often not economically viable. Nevertheless, they do provide significant positive economic effects at a macroeconomic level.

11.6 Mitigation hierarchy

All projects must respect the mitigation hierarchy to target the 'no net loss' principle for biodiversity. This concerns all stages of the project life cycle: design, construction, exploitation, maintenance and dismantling. It is very difficult to assess medium or long term impacts, especially in the context of climate change and territorial adaptation; even more difficult is to determine the ecological equivalence between the ecological impacts and gains associated with restoration operations. In general, the cost, as well as ecological effectiveness, has to be guaranteed.

12 Hydropower plants in marine environment: emerging solutions

12.1 Sea water pumped storage plants

12.1.1 Concept

As the name suggests, a sea water pumped-storage plant is a pumped-storage plant operating with sea water: the ocean is used as the lower reservoir whilst the upper reservoir is located at a high point on the coastline. It is a pure storage and regulation asset. The key benefits of a sea water pumped-storage plant compared to an onshore pumped-storage plant are the following:

- the scheme includes a single onshore reservoir, which allows a reduced onshore footprint, thus limiting the competition for land use and reducing construction costs;
- the plant is fed by seawater, which minimizes the hydrological risk and any competition for freshwater use. The plant can even be implemented in arid desert areas.

Worldwide site screenings show numerous coastal areas combining high solar and wind resources with favourable topography, where sea water pumped-storage plants could bring the required flexibility to the system to allow increased penetration of variable renewable energy sources. Opportunities for hybrid energy and desalination schemes were also identified.

12.1.2 Specific challenges

The main obstacle to sea water pumped-storage plant development is likely to be the environmental and social sensitivity of coastal areas. A thorough assessment of legal restrictions and protected areas should be carried out at site screening stage. Specific technical challenges linked to the use of sea water also have to be faced:

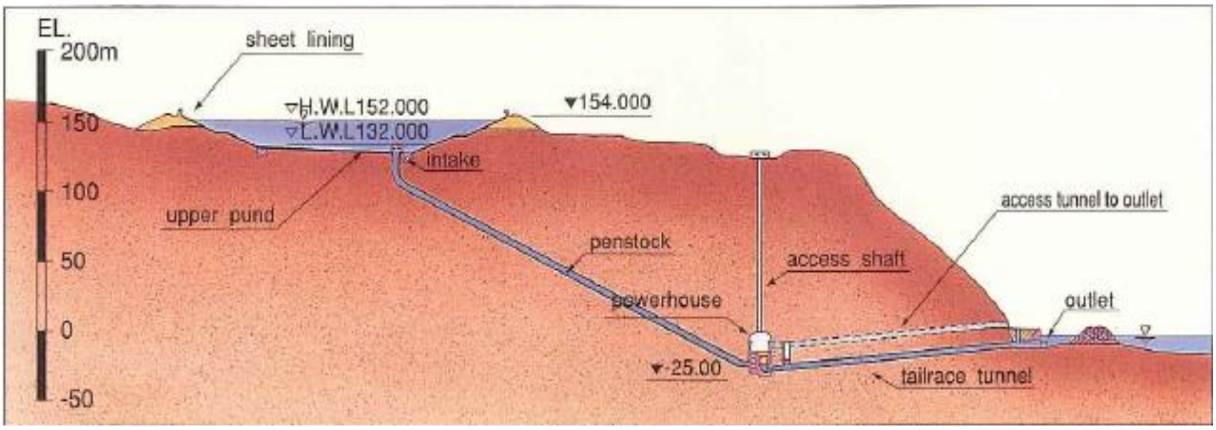
- the upper reservoir and hydraulic circuits should be completely watertight to prevent saltwater infiltration into the soil and groundwater;
- mitigation measures should be implemented to limit biofouling growth on the water intake screens, along the waterways and on the turbine, in order to avoid reduced efficiency;
- corrosion protection strategies should be implemented to prevent the corrosion of steel components in contact with the seawater;
- civil works should be designed to resist extreme marine events and to ensure steady intake and outfall flows, even during storms.

These issues must be addressed in the early design stages but do not represent technological barriers as proven solutions from other industries are available.

12.1.3 Technical readiness level and development status

Okinawa Yambaru was the world's first, and to date the only, high-head sea water pumped-storage plant to have been built and operated in the world. It is located on the northern part of Okinawa Island, in Japan. Details of the plant can be seen in

Figure 12-1 below.



Installed power:	*30 MW*
Effective head:	*136 m*
Maximum discharge:	*26 m³/s*
Upper reservoir effective storage capacity:	*0,56 10⁶m³*

Figure 12-1 Okinawa Yambaru sea water pumped-storage plant.

(a) General view of the site and profile of waterways
(b) Main characteristics
(c) Aerial view

The plant was initially built as a demonstration project for a five-year test period (1999-2004), but after that it was successfully operated until 2016.

Several projects are currently under development, such as the “Espejo de Tarapaca” project in the Atacama Desert in Chile (300 MW) and the Cultana Pumped-Hydro project in Australia (220 MW).

The technology readiness level of seawater pumped storage plants is deemed to be level 8-9.

12.2 Tidal range power plant

12.2.1 Concept

A tidal range power plant consists of a dam enclosing an area of sea which has a high tidal range, along with sluices gates and low head turbines. The sluice gates are used to control the level inside the reservoir so as to create a hydraulic head between the reservoir and the open sea. The turbines convert the potential energy stored by the dam into electricity. Different variants can be considered:

- A “tidal barrage” spans an entire river estuary, such as La Rance power plant operated by EDF (France).
- A “coastal tidal lagoon” encloses an area of the coastline behind a breakwater, such as the proposed Swansea Bay Tidal Lagoon in the UK.
- An “offshore tidal lagoon” encloses an isolated area offshore behind a breakwater.

Other design variants can be envisaged: for example, a hybrid scheme combining a coastal tidal lagoon connected to the open sea with channels equipped with tidal stream turbines was assessed in concept studies and referred to as a “Tidal Garden”.

A tidal range power plant can be operated in various modes:

- **uni-directional operation** (or single action) means that the generation is restricted to either the ebb or the flood stages:
    - **ebb generation**: while the tide is rising, the reservoir behind the dam is filled through the sluice gates. When high tide is reached, the gates are closed. Once the sea level has receded to a sufficiently low level, the turbine gate is opened and the water from the reservoir channelled through the turbine.
- **flood generation**: While the tide is rising the water flows through the

Figure 12-2 La Rance tidal power plant (France, 240 MW)

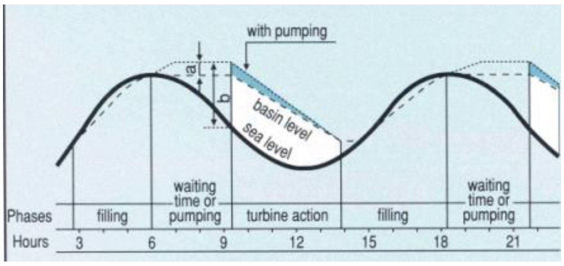


Figure 12-3 Uni-directional operation (ebb)

turbine into the reservoir, generating electricity.

- **bi-directional operation** (or double-action) means that ebb and flood generation are combined, which require bi-directional turbines.
- **Pumping** can also be considered to increase the efficiency. Pumping has been foreseen for the Swansea Tidal Lagoon project in Wales in order to maximise the annual production of the plant. The project is currently on hold (see also Section 12.2.3).

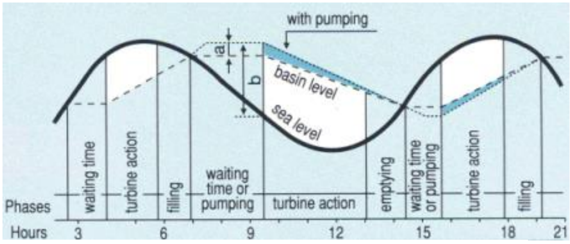


Figure 12-4 Bi-directional operation

Tidal range energy has the advantage that is very predictable, since ocean tides can be foreseen with good precision. Moreover, tidal power plant infrastructure can provide additional public services. For example, La Rance power plant is also used as a bridge for a daily average of 30,000 vehicles. Future projects offer numerous opportunities for multi-purpose schemes providing protection against coastal erosion or flood risk, transport, aquaculture, tourism and leisure activities. Hybrid power schemes combining tidal range, wind, floating PV and storage may also be developed.

The European countries with the highest potential to develop tidal range power plants are the United Kingdom and France.

12.2.2 Specific challenges

The main obstacles for tidal range development are:

- the high levelised cost of energy (LCOE);
- environmental integration of the project, with specific concerns related to the significant modifications of the coastal basin hydro-system (intertidal areas, salt, sediments, barrier effect, etc.);
- social integration: the project should be co-constructed with local stakeholders

12.2.3 Technological readiness level

Five industrial scale tidal power plants are currently in operation in the world, as shown in Figure 12-5. La Rance power plant has been operated by EDF for more than 50 years and still generates around 0.5 TWh/year.

Figure 12-5 Tidal power plants in the world

After decades without any tidal range projects in Europe, new momentum has been observed in the UK with the development of coastal lagoon projects, amongst which we find the iconic Swansea Bay Tidal Lagoon. However, the business profitability of these projects is still weak in the absence of public financial support; therefore, no investment decisions have been taken so far. Feasibility studies have also started to reassess tidal barrage projects across the Mersey and the Wyre estuaries in the UK.

The technology readiness level of tidal power plants is estimated to be 8-9, unless breakthrough technologies are implemented for breakwaters and/or turbines.

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