HYDROPOWER EUROPE

POWERING EUROPE IN A SUSTAINABLE WAY

Hydropower Technologies

The State-of-the-Art

Date:	May 2021
Document No:	WP4-DlRp-57
Version:	v5.0
Status:	Final
Deliverable No:	D4.3
Task Leader:	EUREC

The HYDROPOWER EUROPE Forum is supported by a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 826010

DOCUMENT INFORMATION

Title	Hydropower Technologies: the state-of-the-art
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Distribution	Public
Document Number	WP4-DlRp-57

DOCUMENT HISTORY

Date	Revision	Prepared by	Approved by	Description & status
9/04/19	V1	Emiliano Corà		Document structure
17/06/19	V2	Emiliano Corà		First draft
17/07/19	V3	Emiliano Corà		Consolidated draft
08/08/19	V4	Emiliano Corà		Final document
14/04/21	V5	Andrej Mišech		Updated document

ACKNOWLEDGEMENT

The HYDROPOWER EUROPE Forum is supported by a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 826010

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1 Introduction

Since the late 19th century, hydropower has developed as a clean, safe, reliable and inexpensive source of power and energy services. Hydropower generation correspond 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 the control over the source through its storage capabilities and the greater predictability over wind and solar power of its generation. Hydropower is, however, variable over longer time scales, as it depends on precipitation and water run-off. At 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 mitigate negative effects in term of water availability.

Overall, hydropower has a great potential to enable the transition towards a decarbonised economy in Europe (as it plays an important role in balancing the grid mitigating the negative effects of intermittent generation form 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 rivers' morphology, is also a matter of concern. The hydropower industry has been doing significant efforts to mitigate the negative effect on the environment of hydropower plant and considerable improvement have been implemented in recent years. Although significant progresses have been made in addressing these issues, there is still low level of awareness among the general public on these achievements.

Over the past decades, the 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. Investments into research and development (R&D) are fundamental to meet advances in technology and deal with market competition. Furthermore, to manage environmental and socioeconomic aspects at 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 infrastructures. 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 infrastructures and better operations and maintenance. Finally, the documents discuss current techniques and technologies to mitigate the environmental impact of hydropower projects. Where relevant, current and recent research and innovation projects funded under Horizon 2020 are mentioned, highlighting the objectives of a given project as well as main outcomes (i.e. reports or deliverables).

2 Types of hydropower plants

2.1 Main components of hydropower plants

Hydropower is based on a very simple physical concept. Hydropower plants convert the potential or gravitational energy of water first into mechanical and then electrical energy: the flow of water turns a turbine, which is connected to a generator. The electricity generated flows then to a substation, where the voltage is increased, and then is 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.

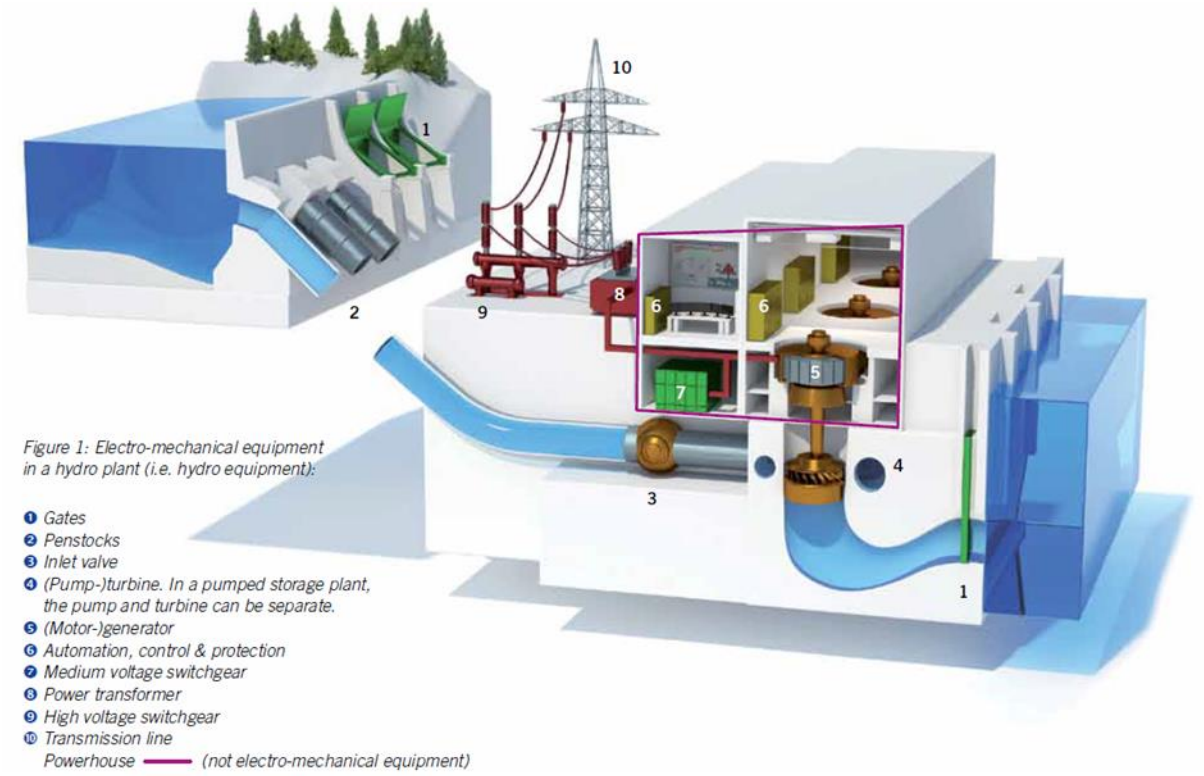

Figure 1 - Electro-mechanical equipment in a hydro plant

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 bear high pressure on the inside surface on occasion of sudden increase and 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 on the rock mass participation can be unlined, lined with concrete or steel lined. Sufficient water head should be provided above the intake entrance to avoid the formation of vortices which may carry air into the penstock and resulting in problems to 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 sudden loading and unloading of the generator with opening and closing of inlet valve and wicket gates. The wicket gates of the turbine allows to regulate the amount of water that flows into the turbine.

The **turbine** is the machine that convert 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 the heart of the hydroelectric power plant. Electricity is generated by the rotating magnetic field created by the spinning of the rotor, a series of large electromagnets, inside a tightly wound coil of copper wire, called stator. The alternating current thus produced is transferred to the **transformer**, which converts it into 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 hydraulic head and volume of the flow rate. **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 needs high flow to generate the same amount of electric energy. Thanks to the higher water pressure, higher heads also allow to force a higher flow rate through a smaller turbine (thus reducing the cost of the equipment). Different types of turbines have been developed, as Pelton, Francis and Kaplan to mention the most often 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 plants:

- **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 categories that match their local energy and resource management needs. In Europe in most of the countries '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 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.

Figure 2-2 – Overview of a storage hydropower plant 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.

In mountain areas, high-altitude lakes can be used as 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. First, they 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 enable them to meet sudden fluctuation in demand. Hydropower plants with a small reservoir are mainly designed to modulate generation on a daily or maximum weekly basis.

2.4 Run-of-river (RoR) power plant

Run-of-river hydropower plants use the natural flow on river of water from upstream 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 incoming river flow. The electricity output of run-of-river power plants depends on 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 sufficiently good for the timescales required in the electricity market.

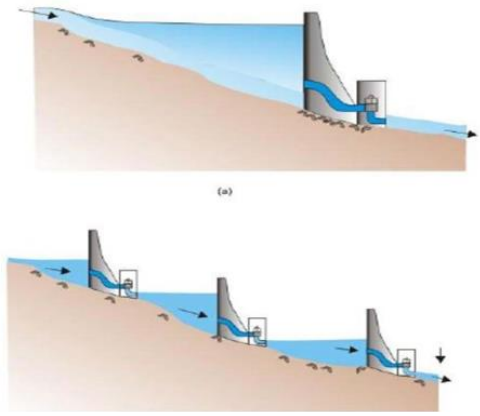

Figure 2-4 -
a) single stage hydropower development scheme
b) cascade or multistage hydropower system

However, run-of-river plants may have some short-term storage possibilities (few minutes dynamic cycle) and this allow 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 large river and small flow rate with 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 according by a simultaneous increase of production in all powerhouses. A storage power plant is often located in the upper catchment as it allows to regulate water flow and 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 to optimise 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 plants move waters 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. As regard 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-turbine 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 an no change of direction is necessary.

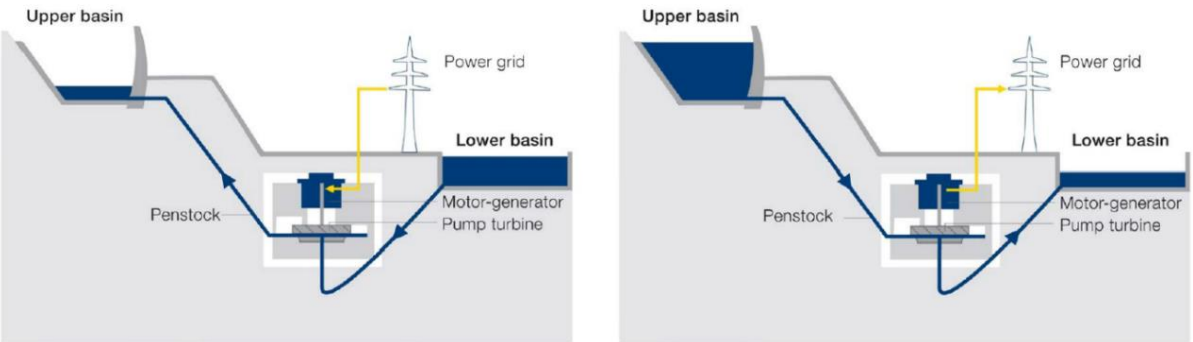

Figure 2-3 - Functioning of PSH in pumping and turbining mode (source: Voith)

Pumped storage power plants are operated depending on 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 on the site's topography and hydrological conditions, existing reservoirs or lakes may be used; if no reservoir 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 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 plants 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 on consumed energy for pumping the water ranges between 70% and 85%. However, this drawback is compensated 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, 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.

Project **ALPHEUS** aims to improve reversible pump/turbine (RPT) technology and adjacent civil structures needed to make pumped hydro storage economically viable in shallow seas and coastal environments with flat topography. It anticipates reaching round-trip RPT efficiency of 0.7 to 0.8 by combining the current state of the art and the expertise of project partners. ALPHEUS will also assess related social and environmental factors, such as fish life, local opinion, and land use.

Three promising technologies will be considered:

- Shaft-driven variable-speed contra-rotating propeller RPT – avoiding guide vanes in a two-way device improves overall efficiency;
- Rim-driven variable-speed contra-rotating propeller RPT – rim driven configuration avoids the complexity of a shaft assembly, decreasing noise, vibrations, switching time, and maintenance costs;
- Positive displacement RPT – fish friendly and seawater-robust, low cost technology.

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 for in-stream technologies include 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.

Project **OPERA** focuses on open-sea wave energy and aims to remove the roadblock (i.e. lack of access to open-sea operating data for wave energy R&D) by collecting and sharing two years of open-sea operating data of a floating oscillating water column wave energy converter. In addition, the project aims to be the first open-sea deployment for four cost-reducing innovations that will be advanced from TRL3-4 to TRL5. Together, these four innovations envisage a long-term cost reduction potential of over 50%. These are: a 50% more efficient turbine, latching and predictive control, a shared mooring system for wave energy similar to those that have reduced mooring costs 50% in aquaculture, and an elastomeric mooring tether that reduces peak loads at the hull-mooring connection 70% and thus addresses one of the most pressing challenges for structural survivability of wave energy devices. The project has produced several public reports, including:

- Mooring Open-Sea Operating Data Analysis
- Recommendations for WEC mooring guidelines and standards
- Turbine-generator set laboratory tests in variable unidirectional flow
- Turbine and electrical equipment performance and reliability in shoreline OWC wave plant
- Open-sea performance and reliability of the OWC turbine and electrical equipment
- Shoreline OWC wave power plant control algorithms
- Open-sea performance and reliability of the OWC turbine and electrical equipment
- Wave Energy Measurement Methodologies for IEC Specifications
- Recommendations to TC114 from real-case applications of wave energy technical specifications
- Uncertainty in Wave Energy Converter Power Performance Assessment
- Extending wave energy converter power quality data set
- Operational model for offshore operation of WECs
- Recommendations and guidelines for offshore operations for wave energy converters

- Operating data input for models UEDIN - Tracking metrics for wave energy technology performance - H2020-OPERA Final Project Assessment and Recommendations
WATEC project deals with the design, fabrication, "on-field" testing and commercialization of an innovative hydro-turbine able to convert into electricity the kinetic and potential energy of waves and the kinetic energy of tidal streams. The technology works in three ways: - it converts the kinetic energy of tidal streams by applying an undershoot waterwheel principle utilising a flow diverter to accelerate and redirect flow under the rotor; - this deflector also redirects waves onto the upper platform where an overtopping principle converts wave potential energy as flow drains past the side of the rotor; - a similar approach and flow path is used to capture wave kinetic energy. Due to the simultaneous exploitation of both potential and kinetic waves and kinetic tidal hydro-energy in a compact plant and to the technology design optimization, WATEC leads to a LCOE of 71 €/MWh.

2.7 Hybrid hydropower

In addition to the four types of hydropower plants mentioned above, it is worthy to mention the concept of hybrid power plants. In this scheme hydropower work with one or more different types of generation as an integrated unit. Hybrid power plants 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 complete during intermittent times when the sun or wind go down.

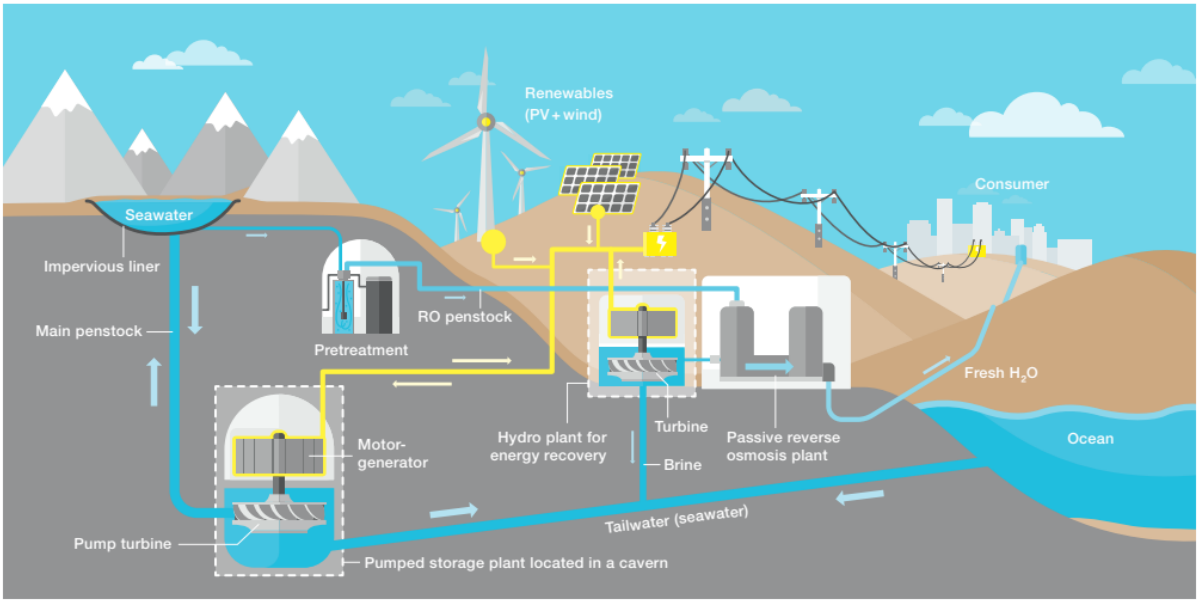

Figure 5 - Exemplification of a hybrid power plant combining seawater pumped storage, plus wind and/or solar power generation, with a desalination (source: Voith)

When pumped storage is possible, it also allows to store excess energy and 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 derive by the combination of hydropower with floating photovoltaic, as the installation of solar panels on dead water spaces allows to maximise 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 shall just describe some of many possible configurations for hybridisation, while other options are subject to further development. These are always tailored to the specific demand for energy and/or water services.

3 Type of hydropower projects

Hydropower plants require high upfront investments but have a lifetime longer than one hundred years. However, electromechanical equipment has a shorter lifespan, but nevertheless very long (40 years or more). Moreover, about 60 % of the economically viable potential in Europe has already been exploited. 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. Second, it is essential to properly investigating the long-term history and variability of an area's water resource 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 investigations of the proposed site's geology, including seismic risk, material availability and sediment transport, are crucial and can greatly impact cost, financing and viability. However, engineering issues are only one part of the equation. It is also critical to consider the project's 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 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, while 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 more efficient turbines and generators. Moreover, retrofitting the power plant using generating equipment with improved performance often enable to answer market demands for more flexible, peaking modes of operation. Furthermore, hydropower infrastructures as intakes and

waterway systems (tunnels, penstocks) can 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 been built most often to serve only one of the above-mentioned purposes. However, due to the increasing demand for these provided 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 with 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 yield 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 **reliable water supply** to municipal and industrial water use;
- using storage reservoir to **maintain a sufficient channel flow downstream** to allow navigation offsetting seasonal variation;
- exploiting reservoirs for publicly **recreational benefits**, such as boating, swimming and fishing;
- storing all or a portion of flood waters and release these controlled and slowly over time to **prevent flooding and drought**.

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

A multipurpose project can be a greenfield project or the result of the upgrade of existing infrastructures. In any case, while planning a multipurpose project it is important to understand the project's purposes and their relative compatibility; in fact, the more compatible these different uses are, and the longer and more in-depth are the consultations before commissioning, the easier becomes the management of a reservoir. Three type 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. Long discussions between all water users, eventually create a consensus between the stakeholders.

- **conflict in time** may arise when water use patterns vary depending on 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 consumptive use at the same time, and the amount stored is not sufficient for all of them. This is the case when reservoir's purposes are power generation and consumptive uses. Since releases for the two 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 securing water volume for 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 that 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 ICOLD register, about 20% of large dams and reservoirs in the world are not used for hydropower generation (Voith, 2017). Powering existing infrastructures offers a great potential to increase hydropower generation. Most of these infrastructures are relatively small in size and have 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, such as Andritz Hydro's HYDROMATRIX® technology and Voith's StreamDiver™, are a good option in this case. These technology consist 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 on 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 Infrastructures

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 dams:

- **diversion dams**, which use diversion systems to keep water surface at constant level and avoid changing 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 river regime and keeping 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 reservoir**, 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, while 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 in conventional concrete or in roller compacted concrete (RCC).

Embankment dams are designed by considering different design 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's 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. The dam is built in the shelter of 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 watertight the foundation 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), an 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 system and operating procedures ensure safety. Pore pressure cells, displacements benchmarks and water flow rate weir are regularly monitored. .

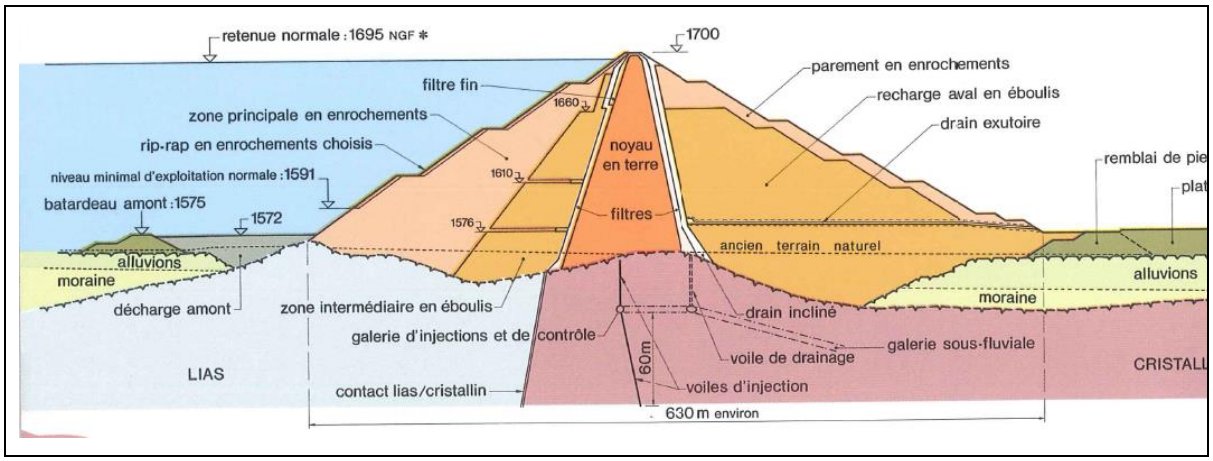

Figure 4-1 - Embankment dam with a core of impervious material (clay and silt)

Arch dams are **concrete dams** that curve upstream toward the flow of water. They are generally built in narrow valleys, where the arch can transfer the water's force to the river banks. Arch dams require much less concrete than gravity dams of the same length, but they require a solid rock foundation to support the loads. At the dam base, a grout curtain reduces the seepage, while a drainage curtain reduces the pore pressures and the uplift force. Main arch dam designers are in Europe. 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. The future challenge for the next decades is the demonstration of its resilience.

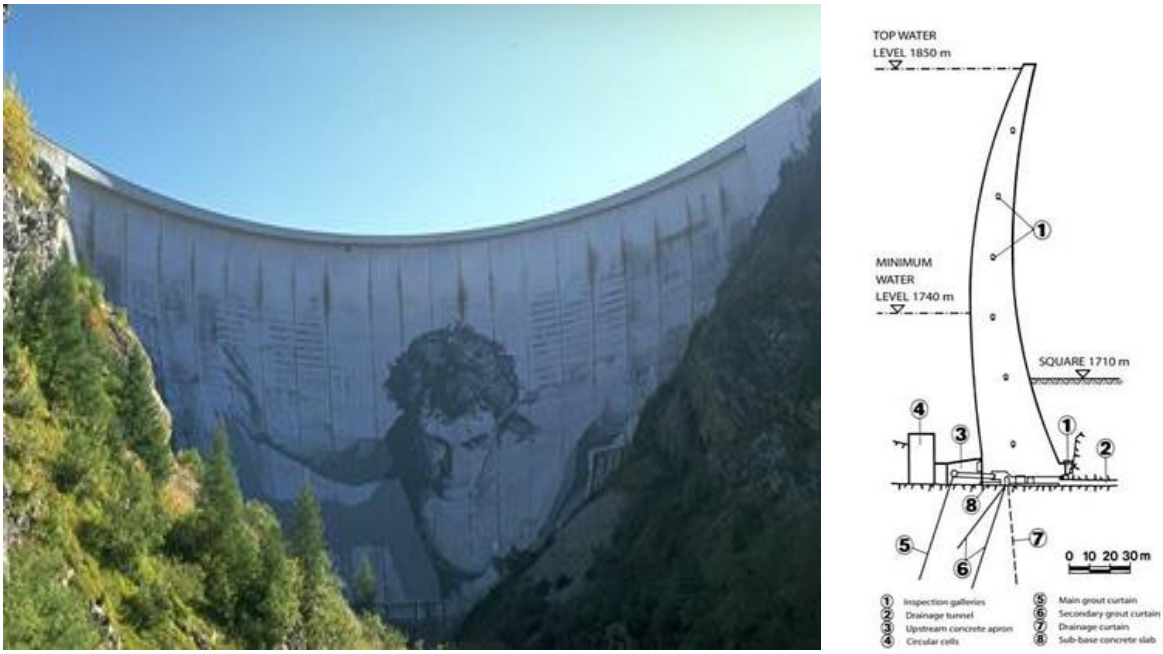

Figure 4-2: Tignes arch dam EDF (left) and typical section of an arch dam (right)

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

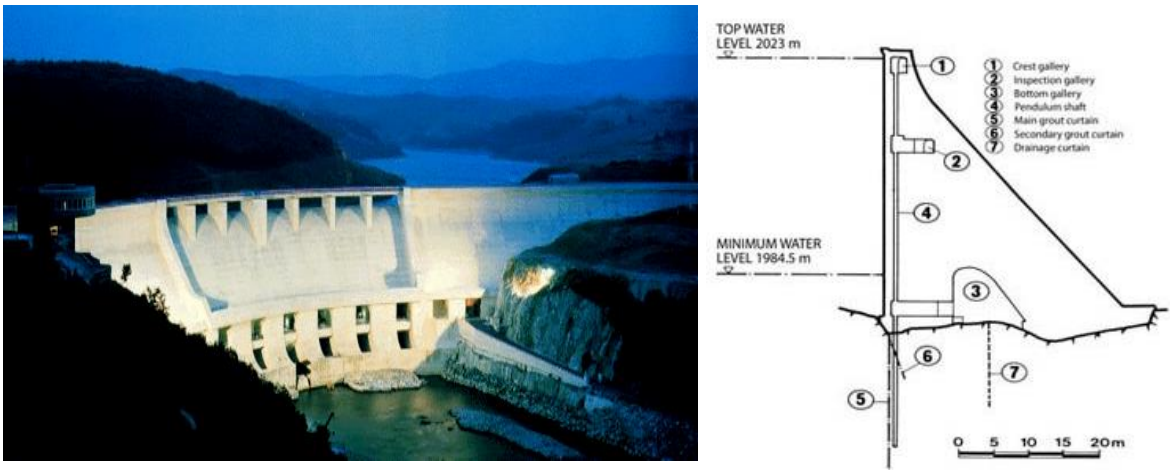

Figure 4-3: Villerest Gravity dam (left) and typical section of a gravity dam (right)

Run-of-river mobile dams are gravity dams built in the river bed 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 riverbed;
- **intakes structures** for conveying water to the power plant;
- **bottom outlets** for reservoir emptying in case of safety problem;
- **spillway structures** to control the reservoir level during floods, in order to prevent overtopping and failure of the structure;
- **fish passages or elevators** for fish migration.

4.1.2 Diversion structures

During construction, the river needs to be diverted to allow the erection 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 flood. There are two main types of structure: **diversion tunnels** or channels (aqueduct). 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.

The 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 to 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 structures to be visited and maintained;
- flushing out sediments from the bottom of the reservoir;
- spilling part of the large floods as auxiliary spillway.

Bottom outlets generally consist of one or more steel or concrete pipes crossing 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 to vary the flow rate. 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 the excess water in a controlled way. The spillway allows flood flows to pass through 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 levels. A spillway essentially has one or two portions: (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 on weir is parallel to the river flow, is the standard and simplest structure, with direct connection from reservoir to tailwater. It is often used on gravity and arch dams.
- **side channel**, whose overflow on 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 to increase several times the discharge flow compared to a frontal weir for a given reservoir level.

The **chutes** could be:

- 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.
- cascade spillway (on the downstream face of gravity dams), dissipating energy on concrete stairs.
- absent, the inlet is the outlet on the crest of 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 condition, 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, either mechanically or hydraulically operated. Three types of gates are currently used:

- **radial gates** are the most frequent on large structures, because they are easy to move;
- **vertical gates** require heavy lifting devices and large and resistant slots;
- **flap gates** are used for small heads and 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: simple, reliable, 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, large floods and large maintenance teams.

A combination of un-gated and gated spillways, adding the advantages of both, is 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 by sole gravity if the reservoir reaches a threshold level. The fuse gate does not rely on 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 need to be replaced after the flood.

4.1.5 Dissipation structures

The energy is almost always dissipated by a sudden slowing down of the flow and a concomitant 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 in a structure, so called the hydraulic jump basin, whose geometry is determined from theory and physical tests. Alternatively, the turbulent flow may be thrown up into the air above the river channel as a jet or nappe. The change in flow conditions occurs in the scour hole or plunge pool. 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 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:

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

The structures for fish migration concern upstream migrating fishes (such as salmons). There are four types of them:

- fish ladder for low head dam, artificial river with a very slight slope (3 to 5%), are more effective than is the old lateral channel where the water is braked by transverse walls;

- fish elevator for high head dam is a tank equipped with a mechanical lifting system that moves fishes from downstream to upstream. Fishes are attracted to the tank by the filling current from the tank;
- fish passes for medium head dams (<30-46m) are 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 lock has two chambers connected by an inclined gallery. Fish move up from the downstream chamber to the upstream chamber by closing the downstream valve;
- Whooshh Fish Passage System (WFPS) uses a pressurised tube to transport fish over dams of any height. It can be adapted to local requirements, while the entrances and tubes can be adapted to migration of various species. It uses multiple cameras to scan incoming fish, which can be used to select which species are allowed to migrate upstream.

This topic is further expanded in chapter 11.1.

4.2 Water conveyance system

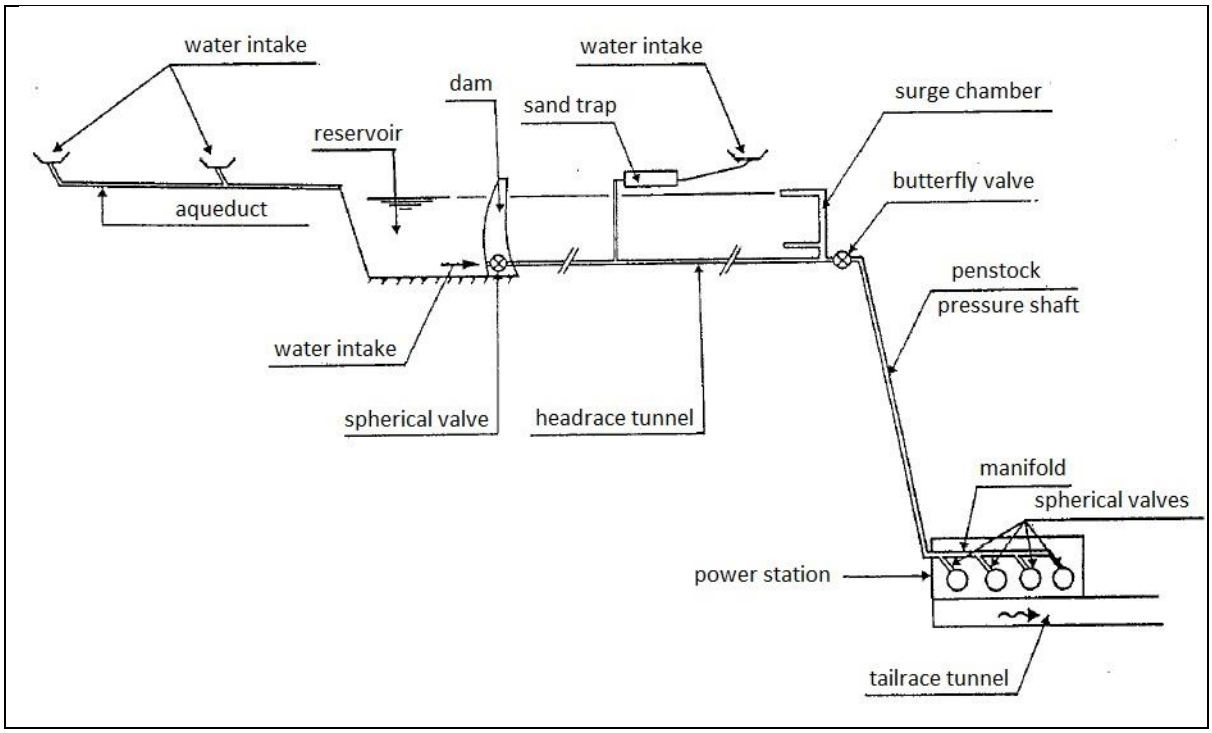

Figure 4-4 - Water conveyance system for Hydropower

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, the solids carried out by the water. The river intakes generally have three main parts: (1) an inlet designed for maximizing the flow rate, (2) a gate for controlling the derivative flow rate and (3) solids disposal facilities for taking the water and releasing in the river the sediments. 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 hydraulic circuit for maintenance. Among the three types

currently used, the 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, while 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. The debris, like floating woods, are 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. The 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 storing the gravel. The gravel is cleared annually or after each large flood by a mechanical shovel. A gravel trap is a channel laterally placed at the weir upstream toe, into which the 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 velocity of the water is 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 evacuated 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 in 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 on the type of hydropower scheme. For plants located in the riverbed or at the foot of the dam, the length is short, while for low head installations whose plant is in 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 on the mechanical characteristics of the materials. The velocity of the water in the channel is designed so as not to cause erosion of the superficial 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 on 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 cement injections.

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 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.

Project **ECO-DRILLING** has envisioned to prototype, pilot, and commercialise a cost-effective and environmentally friendly full profile directional drilling technology for the global hydropower sector. ECO-DRILLING´s solution is capable of drilling upwards over long distances and high heads (up to 2km drilling length-1km altitude difference) using a non-rotatory drill string. This disruptive technology has the potential to cut annual CO2 emissions with 13,860 tonnes in 5 years according to the sales projections, reducing the environmental impact of drilling operations (e.g. by eliminating the need for building temporary access roads to the mountain top), and drilling costs by 50%. The project´s solution aims to support the development of hydropower plants at locations currently unfeasible due to technical or environmental challenges.

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 rooms** hosting turbines and draft tube, 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 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 in a cavern.

5 Electromechanical equipment

Hydromechanical equipment manufacturer are under strong and growing pressure to innovate. In Europe, the EU's decarbonization agenda is requiring 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 in 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 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 an 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 convert 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 on 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 turbine**, which 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 turbine**, whose rotor 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 are the **hydrokinetic** or **free-flow** turbines without any pressure casing and draft tube.

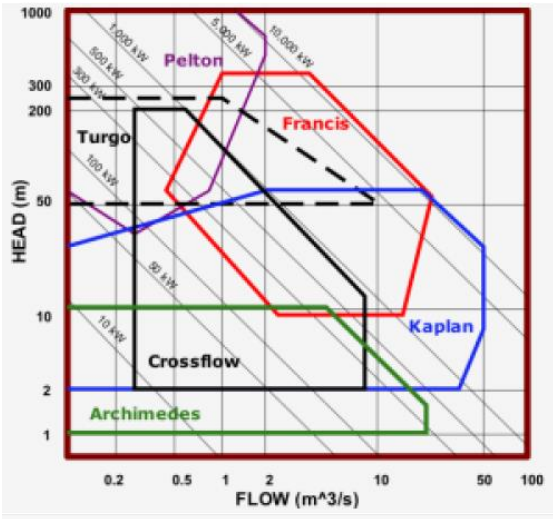

Figure 5-1 - Use of turbine types by head height, discharge, or capacity

- **Gravity turbine**, which is driven simply 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 ranges of head, flow and power applicable to the different turbine types are summarised in table 5-1 and figure 5-1. These are overlapping, just a rough indication and depend on the precise design of each manufacturer as well as of the specifics of a site.

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, either it 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 decades, huge progress was made in turbine development. There has been a trend towards bigger turbine units, higher peak efficiencies and hydraulic performances, e.g. better efficiency over the whole operating range (head/discharge).

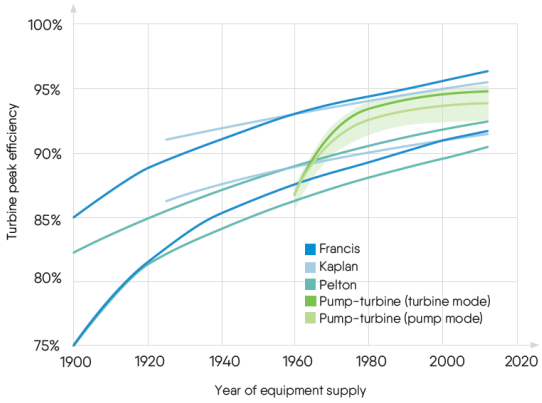

Figure 5-2 - Evolution of turbine peak efficiency over the years (source: Eurelectric/VGB PowerTech, Hydropower Fact Sheets, 2018)

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 successfully implemented.

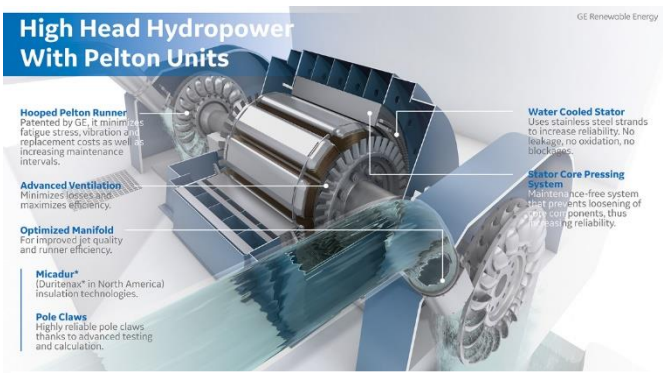

Figure 5-3 – Pelton turbine (source: GE)

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

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 Pelton).

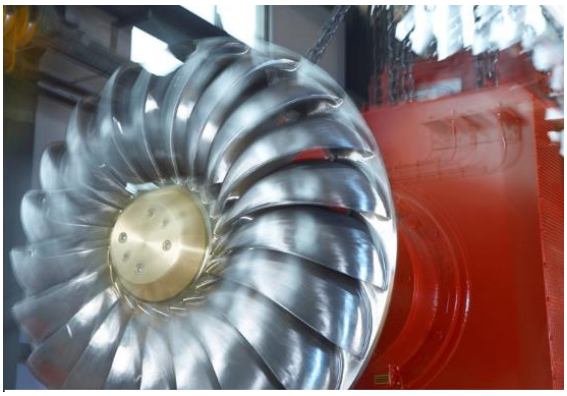

Figure 5-4 – Turgo turbine (source: Wasserkraft Volk AG)

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 the 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. Crossflow Turbine is made for heads of between 2.5 and 200 meters and it is available with outputs of up to 5 megawatts.

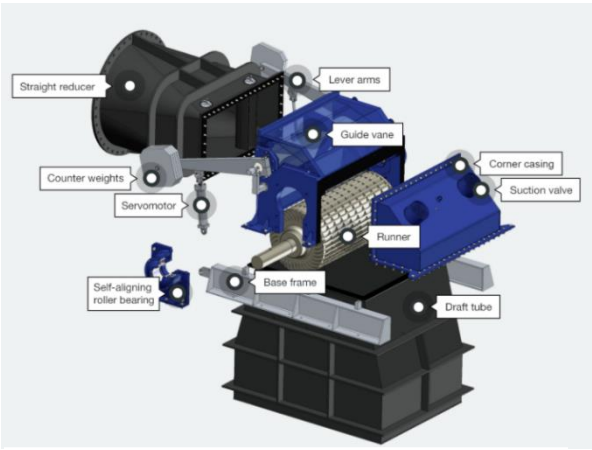

Figure 5-5 – Cross-flow turbine (source: Ossberger)

It starts producing energy already with a very small quantity of water and outstandingly deals with varying flows. This can be achieved with two cells inside the turbine working independently of one another. 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.

5.1.2 Reaction Turbines

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

Propeller Turbines

A propeller turbine generally has a runner with three to six blades in which the water is constantly in contact with all of the blades. Through the pipe, the pressure is constant; 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 turbines:

- 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.

Figure 5-7 – Alden turbine (source: Voith)

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%.

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 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 5-8). 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”.

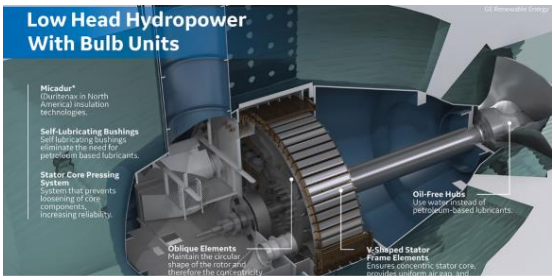

Figure 5-8 – Bulb turbine (source: GE)

The application of bulb and pit turbine units has unique advantages. Their design provides good accessibility to various components and assures reliability and 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 30 m, 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 with more than 95 %. The runner diameters can reach up to 10.000 mm.

Figure 5-9 – Kaplan turbine (source: GE)

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 to adjust the water discharge and turbine output (see Figure 5-9). 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.

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 up to 600 m 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. Generally, such turbines are 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 5-10 – Francis turbine (source: GE)

A Francis turbine has a runner with fixed buckets (vanes), usually in the number of nine or more (see figure 5-10). 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.

Project **Turbulent** is developing a cost-efficient microhydropower plant designed to use a very low head stream without impact. It does not require a dam and is smaller, lighter and easier to install and maintain, while using the natural flow of rivers with interconnected small turbines that generate up to 100 kilowatts of electricity each to form an energy solution up to a few megawatts. The aim of the project is to promote microhydropower and expand the technology in the EU and abroad. The project utilises the vortex turbine, which is declared to be very durable, low maintenance, fish friendly, easy to install and having long operating life.
Project **HYDROGO** examined feasibility of developing mobile, small, easy- and fast-to-install hydropower solution, designed to alleviate the electricity needs of individuals or communities by producing electricity from river currents and waterfalls, efficiently, and in locations where existing

solutions cannot. _Two models were developed based on the same technology: Euro-pallet mounted Drop&Go and container-based Plug&Go to meet micro (<100 kW) and mini (<1MW) electricity demands, respectively. The HYDROGO plants can produce current effects up to 600 kW, meaning that Plug&Go could power up to 1,350 households/year. Practical and theoretical testing has allowed to develop a prototype, which produces at least 20% more energy per waterfall height than existing hydropower technologies. The prototype requires only anchoring but no building work for its installation and is highly customisable to user needs, can be easily relocated, and set-up as a hybrid power station as well as connected to the grid. This solution is not immersed in streams and therefore undisruptive to the environment, easy to maintain and move, if needed. Amongst its many potential applications, HYDROGO is ideal solution for difficult to access areas and disaster zones where off-grid power is needed immediately.
Project **RIVER-POWER** examined feasibility of a disruptive technology able to efficiently convert the water flow kinetics energy in electricity thanks to a turbine innovative design derived from the wind power technology. The new technology enlarges the hydropower potentialities, being able to exploit the zero-head water flows with mini-micro applications (nominal power < 1 MW) and thus allowing the exploitation of new electricity production sources. The project´s initial objectives include: - producing the zero-head kinetics energy driven hydroelectric turbines with the following technical targets: production = 4200 kWh/kW; efficiency = 45%; electricity production cost < 7 c€/kWh; investment < 2.000 €/kW; trigger speed < 1 m/s; minimization of the environmental impact reducing the civil works; easy and cheap installation; - fabricating and testing an integrated prototype (nominal power = 50 kW), to be proved in operational environment, in order to reach the TRL 9 at the end of the testing phase; - industrializing the RIVER-POWER plant, protecting the intellectual right and launching the technology industrial production and commercialization.
Project **HyKinetics** examined optiomisation, "on-field" testing and commercialisation of an innovative 3-blades axial hydropower turbine, specifically designed for application on rivers and able to competitively exploit the hydro-kinetics energy of the water flows without the need of upside barriers. Therefore, differently to existing solutions, HyKinetics would apply for zero-head installations, i.e. without any fall or dam required, and would be characterized by a very low impact thanks to: - The slow rotation of blades (no impact on the fluvial fauna). The small dimension of the blades in respect to the rotational radius avoids abnormal waves and undercurrents. - The turbine is not fixed to the river bed but anchored on the river bank (no drilling needed but floating barge easily removable, no impact on the river bed); - Energy supply and distribution systems are fully immersed, while on the surface there are only the parts needed for maintenance (no visual impact).
SMART SlowFlow is a hydro-kinetics micro hydropower solution, able to reach LCOE (20 c€/kWh) and maintenance cost (<0.25 c€/kWh). The hydro-turbine is integrated in the micro grid smart systems produced and already commercialized in the rural electrification sector (40 grids already sold in Peru, Colombia, Nigeria, Germany, etc.). The technology has been already validated with the first 280 W prototype, proving the performance in terms of cut-in speed (0.6 m/s), reliability and easiness in transportation and installation. A preliminary End-Users benefits assessment showed that the simple pay-back time for micro-grid installation is < 2.5 years.
Project **DP Renewables** has aimed to commercialise a range of innovative, hydrokinetic turbines that will offer a reliable solution for generating zero-carbon energy from rivers, estuaries and canals.

The project comprised of two different sized turbine devices, 25Kw and 60Kw respectively, which are specifically designed to cater to a niche, 'low-power', small-scale energy generation market.
Project **Hydrolowhead** aimed at making the installation of turbines at a micro level more attractive through reducing the large initial investment. It has intended to do so by developing "regenerative variable speed control system" that works at variable speed. The installation time is between 1 and 2 days, reducing civil works by 80%. The pay back for the final clients (e.g. Mini-hydroelectric plants, Aquaculture Companies, Wastewater treatment plants) is 4 years. The final product should be capable of generating the maximum amount of electricity with a constant efficiency (75%) and will be further used as demonstrator plant for our customers worldwide.

5.1.3 Pump Hydro Turbines

Pump turbines can reverse the water flow and operate as a pump to fill a higher located 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 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, also Bulb units can be operated in pump mode, when rotation is reversed.

Pump turbines, with their ability to master rapid mode changes, are ideally suited for generation as well as storage of energy, predestined 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.

The pumped storage technology can switch between the pumping and generating mode within 20 to 30 seconds. This can be realized thanks to fixed speed reversible units, variable speed pump turbines or ternary pump turbine units. It is the large-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 so application operators are fully satisfied. 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 clever shape of the helix allows the turbine to rotate faster than the equivalent waterwheel and with high efficiency of power conversion (over 80%).

However, they 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.

Figure 5-14 – Archimedes screw

5.2 Generators, transformers and high voltage equipment

Generators convert the 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 calculation methods and optimized manufacturing procedures and materials.

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

- **Horizontal** vs **vertical**: hydro generators are classified by their axis locations.
- **Brushless excitation** generator with rotating exciter machine vs **static excitation** with sliprings and brushes.
- **Synchronous** vs **asynchronous generators**: **ynchronous 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 speed rise 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 in the power network. This is of growing importance, as increasing volatile renewable energy sources like PV cannot provide inertia while the share of big thermal based is decreasing.

Synchronous generators and **induction generators** are used to convert the mechanical energy output of the turbine to electrical energy. Induction generators are used in small hydroelectric applications (less than 5 MVA) due to their lower cost, which results 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, while 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 existing experiences with vertical generators for 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 stand for 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, providing 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. It 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 synchronous speed. The units can be started with static frequency converters (SFC), a pony motor, a start-turbine, or back-to-back (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 do not allow to adjust the pumping power, thus preventing the optimal use of surplus energy. Variable-speed motor–generators allow to overcome these flaws 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. Find more details in Chapter 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, cables, to transmit electricity to the grid. These devices are not specific to hydro market. Significant efforts are aimed to improve life duration, minimise the environmental impacts, reduce fire risk, as well as adapt them to eco-design or grid code requirements.

The first concern regarding transformers is to improve safety regarding fire risk. Feedback analysis and investigations of the transformer fleet and others electric equipment is performed to get a better understanding of the risk of failure. Recent developments involve monitoring systems that gives real

time information about operating condition of the equipment. For example, online gas analysers are installed on power transformers to detect problems and prevent failures.

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

In hydro power plants efforts are put on reliability of transformers and high voltage devices, in order to maximize their availability and to fit specific operating conditions 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, miter, 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 safe, environment friendly generation of electric power. The fate of both today's world and of the future depends on 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 on the location where such valve is 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 large damage in case 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 on 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 of outside energy, even against unidirectional pressure at maximum flow rate.

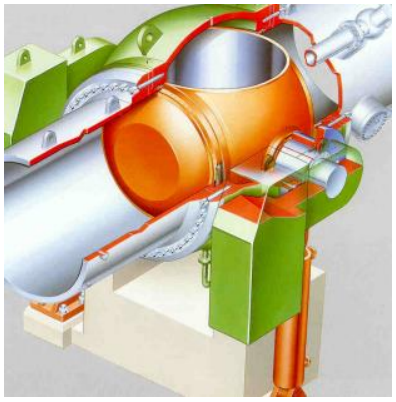

Figure 5-15 – Spherical valve

The spherical valves consist 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. Be it at the intake, in the headrace line, at the start of the penstock to protect against rupture. Butterfly valves are optimally suited to critical situations and stand out due to their performance and low-pressure loss, with absolute impenetrability in all operating conditions.

Figure 5-16 – Butterfly valve

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 seal in all operating situations. The self-lubricating bearings are maintenance-free and the bearing seals can be replaced from the outside.

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 hammering in 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 water or oil hydraulically via an electronic positioner. Additionally, the axial piston‘s 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 5-17 – 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 applied also as pipe break valves, drain valves and, safety valves.

Figure 5-18 – 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 centered 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 lower heads than 75 meters ring valves are delivered without 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 5-19 – 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

Figure 5-20 – Bypass valve

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.

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.

The hollow jet valves made from high quality steel, in combination with an elastic/metal seal and an integrated jet deflector, facilitate cavitation- and vibration-free energy dissipation.

Figure 5-21 – Hollow jet cone valve

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 volume.

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. At hydraulic power plants where short closing times are needed on turbine guide vanes and jets due to technical reasons, pressure relief valves are integrated into lines in order to hinder mechanical over-rev and excessive pressure increase. 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 5-22 – Pressure relief valve

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

Housing and inlet elbow 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 blocked at 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, environmental aspects, number of penstocks according to the number of machines, diameter, length, pressure, available technologies, civil engineering/piping balance, etc.

Equipment related to penstocks include:

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

The realization 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. 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: 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

Large fluctuations of voltage and frequency, if they occur, 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 stabilise the grid. Pumped storage plants can additionally serve as controllable loads, drawing electricity from the grid to charge 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. Additional, water storage allows the power system to balance variability existing in the load over longer timeframes than 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 its generator unit without the need for external power from the grid, these are best suited to provide restoration an electricity network after a black-out.

To provide balancing power hydro plants operators need to ramp-up and ramp-down production more often and faster as well as frequently start and stop power generation. Flexibility in power generation and storage is here intended as the capability to increase the operation range both in generating and pumping mode, allowing the power plant to operate at deep part load and to quickly change power output and input. Variable speed generators provide an answer to these needs.

However, flexibility implies trade-offs in the design of the electro-mechanical equipment as more flexible designs entail lower efficiency rates. Nonetheless, the consideration

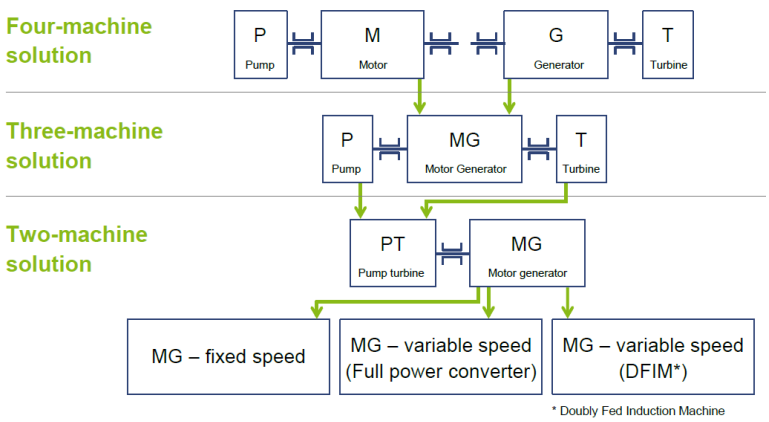

Figure 6-1 - PSP Solutions for balancing services (Voith)

given to the peak efficiency of individual plants is declining relative to the ability of the plant to support the grid. The 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 turbine. Reversible units can rotate in two different direction, depending on the operation mode. 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.

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 to significantly reduce transition time 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 on 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 to have 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 to switch the machine between turbine and pump operation.

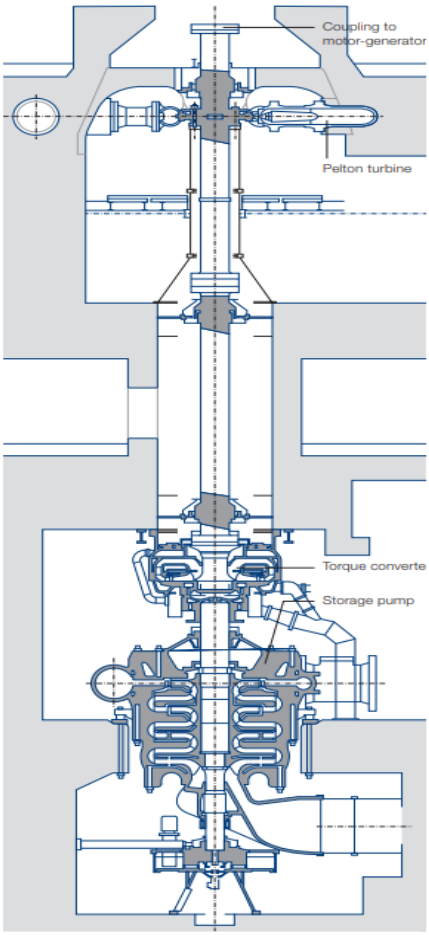

Figure 6-3 - Configuration of a ternary set system

This configuration also makes possible to implement the so-called "hydraulic short circuit" within the machine set, which allows the unit to generate power at the same time it is pumping water for storage. This provides for 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 cost 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.

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 do not allow to adjust the pumping power, thus preventing the optimal use of surplus energy. Variable-speed hydropower generators (motor–generators in pumped-storage facilities) allow to overcome these flaws 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 on the design, variable-speed units may have a narrower rough zone and the ability to generate at lower power levels.

Moreover, 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 capable 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 quickly switch from generating to pumping mode and vice versa.

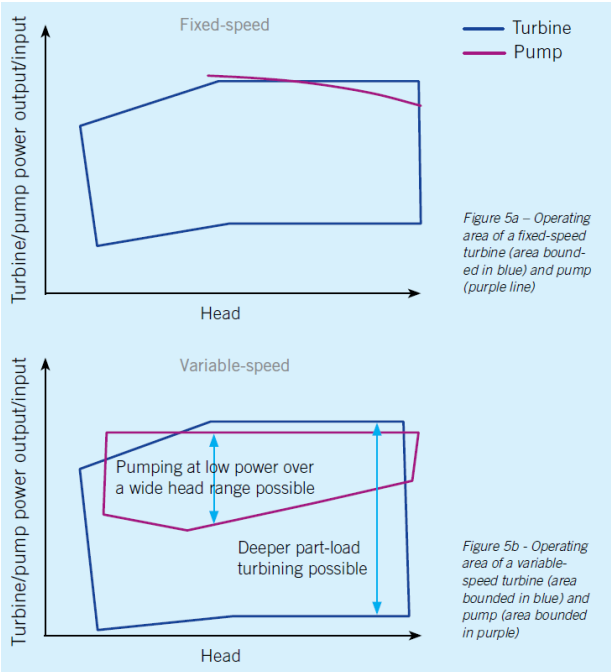

Figure 6-4 – Comparison of operating area of variable-speed and fixed-speed turbines

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. While in conventional hydropower plants the turbine governor has the responsibility to control 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 in 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.

Variable speed operations also benefit to 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 also in case of large head and discharge variation. Therefore, the operating range can be extended. These benefits strongly depend on the plant's operational conditions and hydrology and are more evident where large head variations and partial-load operation occur. Moreover, the gain in efficiency is particularly significant in case of reversible pump-turbine. Since turbine and pumping mode have different optimal speeds, at fixed speed operation of 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, at variable speed operation optimal rotational speed and maximum

efficiency can be achieved in both modes. Finally, operating pumped-storage plants at variable speed does not require frequency converters for pumping startup and synchronization.

The main available solution to realize variable speed operations are doubly fed induction machines (DFIMs) and converter fed synchronous machine (CFSM).

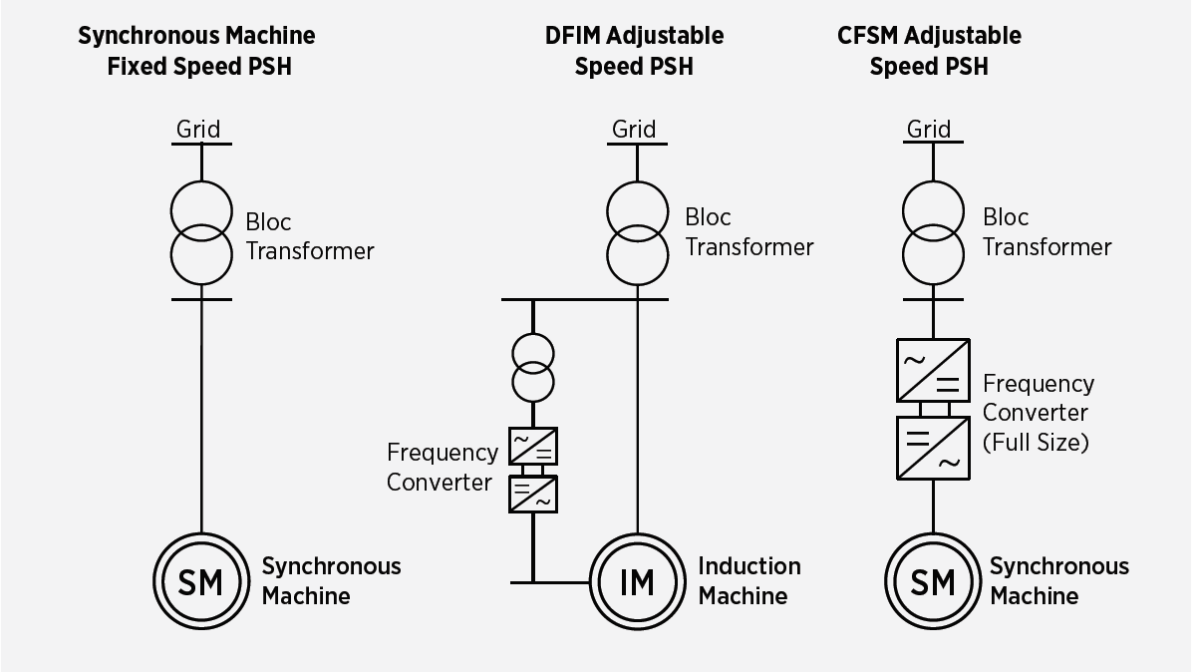

Figure 35: Converter solutions for variable speed operations (Koritarov et al., 2015)

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 startup 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 employ variable-speed technology also in HVdc-connected hydropower plant: since in this case the frequency of the generator is not tied to the grid, the rotational speed can be adapted to optimize the operation of the plant. Moreover, small hydropower plants with considerable head and flow variations can also benefit

from variable speed operations; in this case, variable speed technologies allow to replace rather mechanically complex turbines with simpler ones, while maintaining high efficiency levels.

Project **HydroFlex** has aimed towards scientific and technological breakthroughs to enable hydropower to operate with very high flexibility in order to utilize the full power and storage capability. This is to be achieved through: - Identifying and describing the demands that hydropower plants will be confronted with in future power systems; - Developing a variable speed Francis turbine that accommodates high ramping rates and 30 start-stops per day without significantly affecting the operating lifetime and efficiency; - Developing new power station electrical layouts, generator rotor and magnetization systems, and power electronic converter control for increased flexibility and strong grid support; - Assessing social acceptance and testing innovative methods to mitigate social and environmental impacts. The project has (or will) produced several public reports, including: - Modelling platform for control design purposes and large-scale power system studies - HydroFlex report: Three European Energy Scenarios - Guide with scenarios, exemplary load profiles and recommendations for parametrization - Intelligent control mechanisms for enhanced Fault Ride-Through performance and provision of Ancillary Services - Converter sizing and main circuit component selection for the application - Efficiency comparison of 2-level and multi-level converter - Winding specification and test requirements - Verified design guidelines for end winding electric field grading – Demonstrator - Assessment of public resistance and acceptance to 30 starts/stops
Project **XFLEX HYDRO** aims to enhance the hydropower potential and its capability to provide flexibility services to the grid. To achieve this objective, it will demonstrate an innovative methodology for system integration of hydroelectric technology solutions, and analyse their impact on the modern power market. These innovative solutions will also optimise maintenance intervals, decrease outage times and increase the availability of the entire European hydroelectric power plant fleet. The project has (or will) produced several public reports including: - Flexibility, technologies and scenarios for hydropower

7 Efficient and resilient design

7.1 Causes of inefficiencies

The potential for electricity production in a hydropower plant depends on the hydrology, topography and design of the power plant. Several parameters contribute to determine, within these constraints, the efficiency of the power plant:

- the amount of water available;
- water loss due to 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 change;
- the efficiency in energy conversion of electromechanical equipment.

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

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

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

In addition, the efficiency of plants depends to a great extent on the reliability and availability of the equipment, which can be affected by aging, wear and tear, sudden outages, etc. over the years. 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 also by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow. Therefore, it is important to fast and accurately model turbulent flow and performance at 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 the flows 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 a 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 on electromechanical equipment as many hydro plants have not been designed to provide balancing power continuously. The biggest challenges are:

- frequent starts and stops (20 or more per day for pumped hydro in contrast to 3 per day formerly), and the mechanical and temperature-related stress 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 mechanism;
- 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 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 the sediments may have time to settle, but in run-of-the-river projects most of the sediments may follow the water flow up to the turbines. The traditional solution to the problem has been to build de-silting chambers to trap the silt and flush it out in bypass outlets, but it is very difficult to trap all particles, especially the fine ones. New solutions are being developed by coating steel surfaces with a very hard ceramic coating, protecting against erosive wear or 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 in

minimizing damage from hydro-abrasive erosion to pay off quickly. Therefore, precautions against hydro-abrasive erosion should ideally be taken at the time the plant is designed. Improvements in material development have been performed for almost every plant component.

Project **AFC4Hydro** aims to develop an active flow control system complete with structural health monitoring to improve operation in regimes outside the design window, by reducing pressure fluctuations, loads and vibrations. These improvements lead to an expanded operation window, which allows hydropower to contribute to system services of the electrical grid and to maintain a more natural flow in hydropower schemes, ultimately benefiting the economy, society and environment. Specifically, the system aims to modify the draft tube flow field to mitigate or supress the pressure fluctuations induced by the vortical flow which limits the operation of actual hydraulic machines. Special attention is to be given to the flow instability leading to the formation of the vortex rope in the draft tube. A combination of two innovative technologies is used in the draft tube:

- injection of pulsating momentum (IPM) with a specific frequency, amplitude and phase by means of actuators;
- injection of continuous momentum (ICM) in the form of water jets with controlled speed and orientation directed against the swirling flow.

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 maintenance and operation of hydropower plants thanks to its 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, outage management, as well as condition monitoring equipment. All these innovations have the goal of helping operators building, operating and maintaining the hydroelectric plant at less cost. 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 value of hydropower assets.

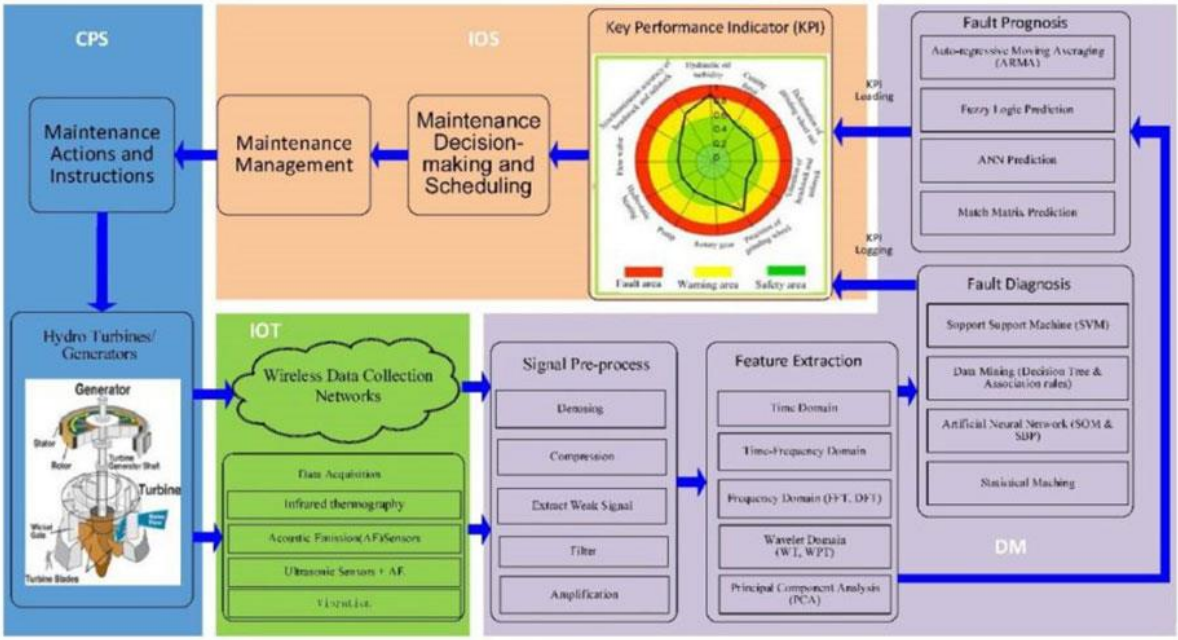

Figure 7-1 - Concepts of digitalization in hydropower (Wang, 2016)

Figure 7-1 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 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 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, at present exploiting the full potential of digitalization in this area 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, cause and effect determination.

8.2 Condition monitoring equipment

Hydropower, as one of the largest and most efficient renewable energy source, contributes to grid stability thanks to its scale of production and its 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 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 to track the health of the plant 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 analyze real-time data, in order to improve diagnostics and prognostics on faults in the plant.

8.3 Outage management

The moment a hydropower plant or unit comes out of service for an outage, it stops generating revenue for its owner and starts racking up expense. 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 the 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 7-2).

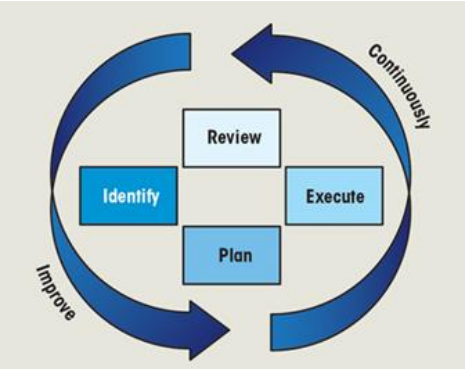

Figure 7-2 - Continuous improvement cycle

To properly manage an upcoming outage - and 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 response, 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 is already planned (with parts on order or already delivered) in order to do unplanned work.

Execution is also a question of scheduling. Scheduling involves knowing how much work is available, how long each task will take, how many labour resources are 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, on-time completion of the outage 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 while 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 for power production plants optimization 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 Computers (PC) resources, Powerline Communications (PLC), Remote Terminal Units (RTUs), smart sensors and data communication and transfer devices. SCADA system’s requirements are:

- up and down openness;
- adaptability;
- real time operating;
- data security and reliability;
- friendly user 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 to analyze data, thus mitigating the risk of investments in energy assets, and 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 the stability to the heat-generation in 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 to 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; it 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 by digitalization. In the last years the digitalization in hydropower has move 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 in the plants, have been recently developed. These systems, also known as “digital twins”, provide prompt notifications of changes in function or performance.

Models and algorithms will more and more 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 a 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 and recreational activities. In order to optimize the use of available water, operations are carefully planned. Expected 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 occurring 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 to process huge number of data and to perform calculations that come much closer to determining risk; in fact, it allows to detect anomalies in a more cost-efficient way and provide the intelligence to make an accurate judgement.

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 plants, especially those delivering balancing power because of the related dynamic operation, dynamic loads and increased wear and tear. Maintenance programs are aimed to reduce or eliminate unplanned equipment failures,

so disruption in electricity generation are 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 (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. This approach helps to prevent major drawbacks.
- **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-centered 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 the first round of completed maintenance feedback is gathered to see if the options were optimal and accurate and adjustments are made as needed. This process is repeated on a regular basis.

While 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 analyzing 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 analyzed 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 tool for asset lifetime management utilizes real-time data for monitoring condition of critical FCRPS assets and enables 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 enables cost-benefit assessment 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 are implemented and installed for monitoring the critical parameters. These instruments can be embedded in the structure itself, during the construction, or installed in its 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 in 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 water reservoir, and the utility structures. Usually, measurements are made on a limited number of control points, properly established in key positions to extrapolate the behavior of the whole structure. In parallel, 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 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 type of sensors are commercially available. Acoustic monitoring systems allow to supervise 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 at dedicated machine parts. Equipped with sound recorder for acquisition, preprocessing and transmission of sound data, and data recorder for acquisition, preprocessing and transmission of process data, these systems allow operator to easily detect anomalies based on frequency spectra and 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 while 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. River system real-time

scheduling modeling tools have been developed for operational decision making, responsive forecasting, flood management and emergency action plan, system optimization, and long-term resource planning. These real-time scheduling tools allow the user to compare several planning alternatives by modeling hydrologic and hydraulic processes, hydropower production, and water quality parameters such as dissolved oxygen, total dissolved gas, and temperature, among other factors. Hydrodynamic and water quality and optimization models 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 water quality constituents.

Project **IMPREX** has addressed the improvement of forecast skill of meteorological and hydrological extremes in Europe and their impacts, by applying dynamic model ensembles, process studies, new data assimilation techniques and high resolution modelling. Novel climate change impact assessment concepts focuses at increasing the realism of relevant events by specific high resolution regional downscaling, exploring compounding trans-sectoral and trans-regional risks, and designing new risk management paradigms. The project has developed four promising novel concepts related to hydro-meteorological risk assessment:

- Novel concept 1: Climate variability and flood/drought risks
    - Report on new methods to enhance seasonal prediction
    - Crop yields and flood impacts derived from large scale climate indices
        - Report on index-based drought risk assessment
- Novel concept 2: Future weather and compound events
    - Inclusion of compound events in risk analysis
- Novel concept 3: Methods to support drought risk management
    - Improvements to the drought risk management toolkit AQUATOOL
        - Report on the application of multihazard risk management tools
- Novel concept 4: Probabilistic impact assessment
    - Mapping impacts of remote climate extremes on food and manufacturing chains
        - Report on dependence of Europe's economy on other parts of the world in terms of water resources

Project **DAFNE** has addressed integrated and adaptive water resources planning and management approach that explicitly addresses the water-energy-food (WEF) nexus from a novel participatory and multidisciplinary perspective. This was to include social, economic, and ecologic dimensions, involve both public and private actors and to be socially inclusive, to enhance resource efficiency and to prevent the loss of ecosystem services in regions where large infrastructures exist or are being built and intensive agriculture is expanding. A decision-analytic-framework (DAF) has been developed to quantitatively assess the social, economic, and environmental impact of expanding energy and food production in complex physical and political contexts, where natural and social processes are strongly interconnected and the institutional setting involves multiple stakeholders and decision-makers. The project has produced several public reports, including:

- Baseline scenario
- Future drivers and scenarios
- A distributed hydrological model to simulate hydrological response, transport processes and sediment dynamics
- Water quality response in the Zambezi River to reservoir management scenarios
- Agricultural productivity in the Omo and Zambezi river basins
- Key ecosystems and ecosystem services in the Omo and Zambezi river basins

- Integrated model of the WEF nexus
- Water quality response in the Omo River to reservoir management scenarios
- Models of the economic development in the Zambezi river basin
- Models of environmental policy in the Omo and Zambezi river basins
- Models of demographic, cultural and social developments
- Models and principles of water governance in the Omo and Zambezi river basins
- Integrated framework of models for social, economic and institutional developments
- Models of the economic development in the Omo river basin
- Evaluation of indicators, value functions and pathways
- Decision Analytic Framework
- Exposure space and failure conditions
- NSL technical implementation plan
- Intermediate evaluation report on NSL operation

Project **SECLI-FIRM** has been demonstrating how the use of improved climate forecasts, out to several months ahead, can add practical and economic value to decision-making processes and outcomes, primarily in the energy sector, but also in the water sector. Specifically for the energy sector, SECLI-CLIM has been assessing the impact on operational planning and portfolio management, such as hedging and asset optimization, thus enabling quantification of the value-add provided by seasonal forecasts which have been calibrated, evaluated and tailored for each specific application. Improvements in management decisions aim to ultimately lead to an improved supply-demand balance and therefore to a more efficient energy system, particularly with respect to renewable energy, with corresponding benefits for climate change mitigation. The project has nine case studies of which the following are relevant to hydro energy:

- Case study 2: Dry winters in northern Italy and energy generation
- Case study 5: Strong El Niños and energy mix planning
- Case study 9: Water management to identify periods of stress to the supply-demand balance

Project **BINGO** has aimed to provide demand-driven solutions for a number of specific climate-related challenges in particular for highly vulnerable water resources of strategic importance to provide water managers and other stakeholders with information on specific climate scenarios at the space/time resolution fitting their needs, enabling them to act at various geographical levels (local, regional and European). BINGO aimed at reducing the uncertainty of climate predictions and developing response strategies to help society manage that uncertainty. An innovative approach consisted of enrolling end-users from the start, identifying specific vulnerabilities, needs and concerns about future climate. The project was built around 7 research sites in Northern and Southern Europe, covering a representative range of climatic conditions as well as combinations of water systems and water pressures. They illustrate a variety of water cycles at local/regional scales in Europe over various timescales, as well as common problems, including floods and droughts; water quality pressured by CSO, agriculture and competing demands for water (urban/tourism; agriculture/food security; hydropower). The project has produced several public reports, including:

- Climate predictions
  - Data downscaled to 12km/daily, Europe, for the period 2015-2024
  - Definition of extremal circulation patterns, present climate
  - Present climate extremal episodes downscaled to 2km/1h / maps of return levels
  - Ensembles for decadal prediction extremal episodes downscaled to 3-1km/ 1h); Spatial stochastic precipitation generator for catchments

- Ensembles for decadal predictions extremal episodes downscaled to 1km1h for Cyprus research site
- Stochastic weather generator producing large ensembles for decadal predictions
- Maps of IDF curves

- Water cycle modelling
  - Characterization of the catchments and the water systems
  - Future Land and Water Use Scenarios
  - Calibrated water resources models for past conditions
  - Model results for water and land use scenarios at the six research sites completed and analysed
  - Improved model applications/descriptions based on field data
  - Optimized water resources models as a support to management strategies
  - Special report on RCP scenarios: Impacts of long-term climate change effects on typical water problems in Europe
- Risk assessment
  - Context for risk assessment at the six research sites, including criteria to be used in risk assessment
  - Indicators of scenarios of risk caused by extreme weather events at the six research sites
- Risk management approach
  - Portfolio of Adaptation Measures
  - Compilation report on initial workshops at the six research sites
  - Report on economic and societal impacts of the proposed measures
  - Report on the assessment of the current governance situation and recommendations for improvement at the research sites using the three layer framework (part 1)
  - Complete Report on the Assessment of the Current Situation and Recommendations for Improvement Using the Three Layer Framework
  - Exploitation of adaptation strategies beyond the research sites
- Ensuring actionable research
  - Guidelines designed to create, feed and enhance "win-win" collaborations between researchers and stakeholders
  - Final portfolio of actionable research problems/challenges exploitation and development

Project **EoCoE** has established an Energy Oriented Centre of Excellence for computing applications, using the prodigious potential offered by the ever-growing computing infrastructure to foster and accelerate the European transition to a reliable and low carbon energy supply. EoCoE assists the energy transition via targeted support to four renewable energy pillars: Meteo, Materials, Water and Fusion, each with a heavy reliance on numerical modelling. These four pillars are anchored within a strong transversal multidisciplinary basis providing high-end expertise in applied mathematics and HPC. The primary goal of EoCoE is to create a new, long lasting and sustainable community around computational energy science aimed at resolving current bottlenecks in application codes, leading to new modelling capabilities and scientific advances among the four user communities; developing cutting-edge mathematical and numerical methods, and tools to foster the usage of Exascale computing. Dedicated services for laboratories and industries are established to leverage this expertise and to foster an ecosystem around HPC for energy. The project has produced several public reports, including:

- Ultralarge Meteorological Ensemble

- Formulation for Optimization under Uncertainty - Improved Gridded Wind Speed Forecasts by Statistical Postprocessing of Numerical Models with Block Regression - Paper on GHI Forecasting - GHI Forecasts at Local Scale - Calibration of Wind Speed Ensemble System Prediction - Porting of Codes and Atomic Scale Congurations - Optimization of Methods - Properties and Characterization of Materials - Application Lines – Benchmark and Results - Analysis of temperature rangese and fluid flow rates in a 3D subsurface model - Layout of an Energy Supply System for Teveren based on Geothermal Direct-heat - Flux Surface Meshing Software-specification report - Tokamesh a Software for Mesh Generation in Tokamaks - Towards the Coupling of Gyrokinetic and Fluid Codes Towards Iter Relevant Simulations
Project **HYPOS** addresses the need for accurate information on key environmental variables to allow better assessment of operational costs and ecological impact for new opportunities in hydropower. this is achieved by providing a suite of data analysis applications integrating Earth Observation technologies and modelling for the hydropower industry. These include an online decision support tool for investment planning and monitoring, as well as a subscription portal combining satellite data over time, current measurements and detailed estimates for present and near future assessments.
Project **Waterjade** aimed to develop a new technology that exploits a range of data sources on weather predictability and satellite information. It aims to help prognosticate the water quantity expected per year with reliable precision. While Waterjade's clients were initially hydropower plants, the project is now starting to work with public and private entities to predict conditions such as drought or avalanches.

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 infrastructures security derive mainly from floods and earthquakes. The priority is, therefore, to increase the resilience of infrastructures against these threats. Another source of risk is the ageing of infrastructures. In the coming decades, more and more infrastructures are going to reach the end of the project's expected life span (100 years) and most of them will need retrofit. Through regular risk assessment, infrastructures' owners can keep risks from natural events under control. Ageing related risks are better addressed through predictive maintenance, which allow to increase infrastructures' 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 infrastructures 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 including new patterns and large dataset and they are now widely used. 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 increased, based on risk assessment. The increase of return period leads to increase of capacity discharge and the need for recalibration of spillways: piano key weirs and concrete or metal fuse gate are the main solutions for spillway recalibration. The flood routing was changed and improved, while innovation has led to new solutions to prevent overtopping, including concrete slabs, shotcrete spillway embedded in the embankment, secondary spillway in RCC placed on the downstream face of embankment. Consideration of climate change effects has been included in the most recent hydrological studies. Shared views on this trend are necessary to strengthen assumptions and results. Finally, verification of the consistency of guidelines adopted in the European countries is one of the most important steps to improve the security of hydropower in Europe.

The rationale to improve flood control of hydropower infrastructures lays in the need to:

- ensure downstream population protection from flood effects;
- increase the level of awareness of dam´s owners and public authorities;
- accommodate climate changes effects; and
- ensure compliance with national and European legislation.

The main impacts for the industry are:

- increasing reservoir flexibility exploitation; and
- maximizing energy production.

10.2 Earthquake resilience

Earthquake resilience is also a priority to ensure infrastructures' 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 increased with risk. It 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 analyses methods, which allow the calculation of the non linear seismic response of embankment and concrete dams, are available; however, their results should be verified with observed data. Most of the 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 be considered**.**

Dams of various types have already been subjected to intense earthquakes with high magnitudes (M $\geqslant$6) and with epicentres at relatively short distances from the dam site. There are several publications reporting theirs effects; it would be very useful to report these feedbacks in a unique European data base and extract from it the best practices to avoid damages caused by earthquakes.

10.3 Risk assessment and civil society protection

The **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 analyses have been developed, from screening level assessments by a few individuals to a significant, in-depth team risk analysis such as with Oroville Dam spillway incident in California, USA. In this context, numerical models are invaluable estimation tools for failure probabilities associated to 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 and an enormous computational time, often unfeasible. Thus, they are limited to very simple numerical models or even to analytical expressions.

Hydropower plants are key **critical infrastructures**, as other facilities depend on the 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 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 infrastructures 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 the largest 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 of Lifetime of infrastructures

Among hydropower projects main elements there are dams, spillways, bottom outlets, hydraulic circuits, intake and outlet structures and powerhouse. The performance of these infrastructures influences the quality of operation and the level of structural, hydraulically end environmental functionalities. Detected anomalies, incidents and/or accidents are indicators of an unsatisfactory performance and the need of improvements. Investments for infrastructures rehabilitation are mainly related to:

- recalibration of design floods and spillway capacity;
- improvement of seismic resilience of dams;
- concrete 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 the Alkali-Aggregate reactions, 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 than decommissioning or replacement have already occurred (e.g., replacement of the Sera Dam in Switzerland and the Alto Ceira Dam in Portugal). Most usual expansions 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 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, monitoring its security and perform structural assessment 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 occurrence and of dam failure, by allowing to assess the dam behaviour, identify potential failure modes, early detection and estimation of the associated risk levels, and implementation of Emergency Action Plans.

Government Agencies have issued pieces of 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, in existing dams instrumentation systems can be obsolete or not reliable and re-instrumentation can be necessary. The risk level of the dam, the criticality of the provided information, the cost and the installation opportunity are all issues to be considered to improve monitoring systems. Extensive new developments in dam instrumentation have emerged and can be applied to existing dams with relatively limited installation work.

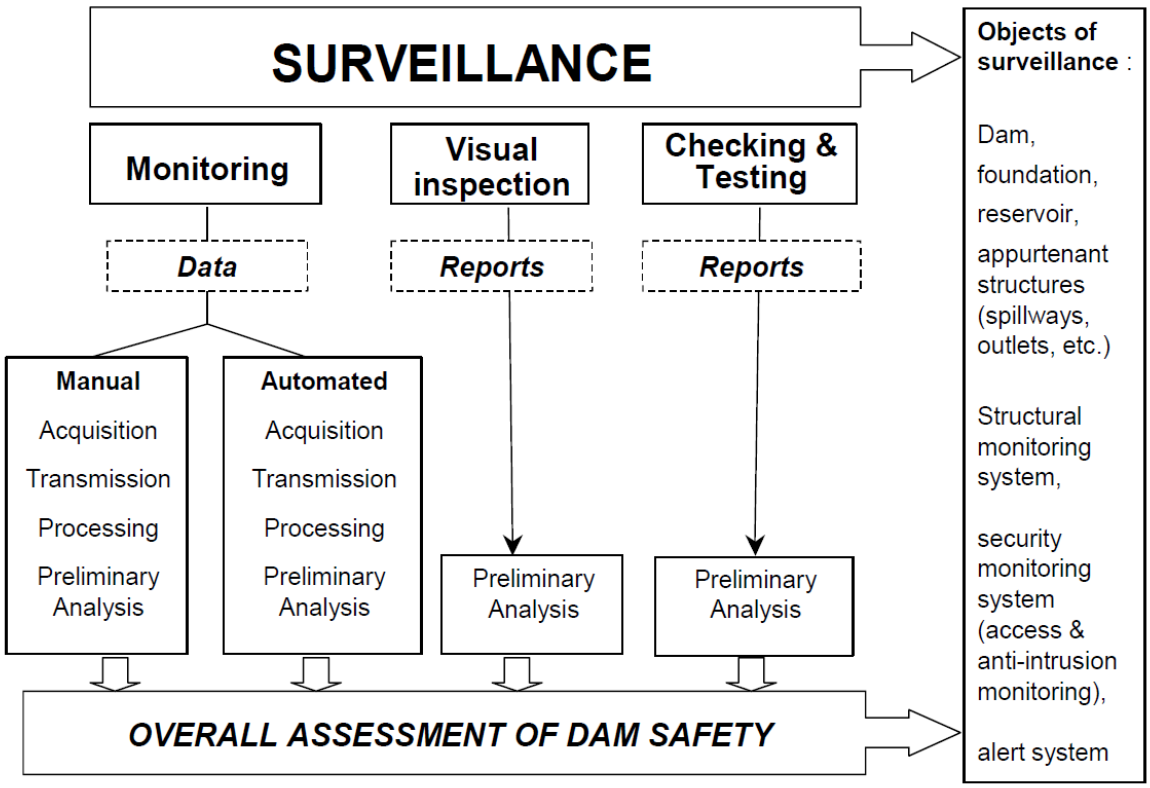

Figure 10-1 – Conceptualisation of dams' surveillance systems

Next to the installation of sensor in equipment and infrastructure, methods for remote sensing also exists:

- satellite images based in InSar technique are used to monitor creep or slow landslide of the river banks;
- drones (UAV) are more and more used to do local topography survey by photogrammetry or to measure the flow velocity;

- 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 that detaches and transports soil particles into a dam or its foundation as a result of seepage. It causes the alteration over time of the materials (desiccation, corrosion of pipes, leaching of masonry, cracks, dissolution, wood decay) and it is responsible for the failure of nearly half of the 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, optical fibers can be installed at the base of the structures, to continuously and remotely monitor the signs of internal erosion (changes in flow rate, temperature and deformations). One of the main challenge for old earthen hydraulic structures is to strengthen and uprate monitoring system, in order to prevent erosion phenomena.

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 structure needs to be further explored. The installation of PVC membrane 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 rule are still used. Tests and analyses are needed for a better understanding and a better use of the rock. The stability of surge tank 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 the flexibility.

11 Environmental and social issues

The development of hydropower projects has both positive and negative environmental and social impacts. Regarding environmental issues, hydroelectric structures affect a river's ecology mainly by changing its hydrologic characteristics and disrupting the ecological continuity of sediment transport and fish migration through physical barriers, such as dams, dikes and weirs. As for the social impact, hydropower may request the relocation of local population, but it is usually a driver of socioeconomic development. Moreover, it may affect land use, the economy, health and safety of local communities. On the other side, local communities may benefit from hydropower projects not only by generating electricity but also by enabling multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts.

The main environmental and social issues related to hydropower projects, as well as the extent of its positive and negative effects, are typically site dependent, since each hydropower plant is uniquely designed to fit the site-specific characteristics of a given geographical site and the surrounding society and environment. As a matter of fact, run-of-river HPPs do not alter a river's flow regime, while the creation of a reservoir for storage hydropower 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 point of view, 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 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 migration needs of fish, especially salmonids and amphihaline European species, are quite well documented (guidelines, feedback of experiences). However, the downstream behaviour of fish is less known (except for salmonids and eels).

Upstream fish migration can only be facilitated with civil works installed on dams (fish ladders, fish lifts, WFPS) 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 population. In case of the Whooshh Fish Passage System, the added value is its use of multiple cameras to scan incoming fish, which can be used to select which species are allowed to migrate upstream (e.g. excluding invasive species, or potentially even identifying wild vs. hatchery fish).

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

- **Fish-friendly turbines**: to achieve this scope turbine design aims to minimize the gaps between rotating and stationary components, create blunt leading edges on runner blades, reduce runner rotational speed; minimize the number of runner blades and/or allow low turbulences.
- **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, turbines shutdown 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 remain important. Fish survival is really site- and species-dependent. Moreover, it needs to be taken into account the fact that fish-friendly design may increase head loss and maintenance costs. Reserving water for fish movement or take plants offline to allow fish migration, implies a loss of revenue for the project owner.

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

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

- where fish migration is (was) prevented due to other (natural) barriers;
- where no suitable habitats can be found or created up-/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.

Project **FIThydro** has addressed the decision support in commissioning and operating hydropower plants (HPP) by use of existing and innovative technologies, concentrating on mitigation measures and strategies to develop cost-efficient environmental solutions and on strategies to avoid individual fish damage and enhancing population developments. The project has produced several public reports, including:

- Cumulative Impact Assessment
- Guidelines for fish behaviour assessment at HPPs
- Enhancing and customizing technical solutions for fish migration
- General cost figures for relevant solution, methods and tools
- General strategies to optimize production under given environmental restrictions or measures that influences production schedules

- A set of general applicable effectiveness measures for solutions, methods and tools implemented to improve fish sustainability in regulated rivers and a cost-effectiveness matrix for a set of combined solutions, methods and tools - Overview of relevant information on cost-effectiveness in regard implemented and possible measures to maintain or improve sustainability of fish population in the selected case studies - A cost-effectiveness matrix for the selected case study rivers and a similar matrix for potential new hydro power schemes of different characteristics - Decision support system integrating technical solutions and guidelines from WP2 and 3, cost-effectiveness from WP4 and social-political aspects from WP5
Project **KEEPFISH** has aimed to improve the passage of vulnerable fish species through river barriers in temperate regions of the southern hemisphere currently experiencing rapid hydropower development. This has been done through a systematic attempt to bring together world-leading practitioners from Europe with biologists, engineers and stakeholders from the southern hemisphere in an effort to exchange knowledge and construct a shared vision for fish passage science and policy. This has been achieved through systematic review, expert consultation, ecological modelling, training programmes, networking and stakeholder engagement using a novel combination of approaches. The outcomes has included: high quality journal publications; a summer school; a set of funding bids based on a co-constructed research strategy; and a model predicting fish passage for species of the southern hemisphere.

11.2 Sedimentation

A river's sediment load is composed of sediments from the riverbed and sediments generated by erosion in the drainage basin. By reducing current velocity and the slope of the water body, dams decrease rivers' sediment-carrying capacity. Sediment deposits in the reservoir reduce its storage capacity and could lead to the raising of riverbed and an increase in flood risk. Additionally, retention of sediments in 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 reduce are aimed to lower these risks. Regarding **fine sediments**, mechanical or dredging-dilution extraction are current (but expensive) practice. However, the impacts on salmonids and other species and therefore the determination of a pilotage threshold for a sediment management operation remain very difficult to assess. In case of **gravel sediment**, dam transparencies (flushing) may be operated on torrents with a high level of coarse transport. But this is not always possible. Where gravel sediments are missing downstream dams, **restoration of the river morphology** may be implemented, to mitigate the riverbed incision and reduce the risks for riverine.

11.3 Water quality

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

The changes in water quality in reservoirs depend on the residence time of the water, the thermal stratification, the sediment quality and the quality of the incoming waters, which depend on the geological context, land uses, nutrients concentrations, climate, etc.). Since these factors cannot be directly managed, 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 are: site selection, appropriate design, future reservoir morphology and hydraulic characteristics. Hydrodynamic and eutrophication models may be used to help understanding how the reservoir water quality may evolve under specific conditions.

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

The emission of greenhouse gases from large, young and deoxygenated reservoirs may also be an issue, even if this is not very frequent 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 in some dam management operations, like 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.

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

Project **SHYDRO-ALP** proposes a multi-disciplinary investigation to better quantify hydrological alterations from SHP and its effects on Alpine stream ecosystems. Combining field-experiments, surveys and innovative modelling of existing flow data-series, the project: i) quantifies the spatio-temporal scales of hydrologic alterations associated with SHP using integrated analytical tools and modelling approaches applied to long-term, spatially distributed data; ii) experimentally mimics water abstractions from SHP using semi-natural flumes to assess the response of aquatic invertebrates and the link between community assembly and ecosystem function applying the Price Equation partition; iii) quantifies flow-ecology relationships and the cumulative effects of multiple SHPs using novel functional regression models with streams hydrographs. The results provide new

insights into the short- and long-term effects of SHP on Alpine streams, with practical implication for the sustainable use of water resources.
Project **RIBES** aims to train 15 Early Stage Researchers (ESRs) in the interdisciplinary field of Ecohydraulics to find innovative solutions for freshwater fish protection and river continuity restoration in anthropogenically altered rivers. The 15 ESRs will carry out an innovative and integrated research programme within a multidisciplinary and intersectoral Network, including 8 leading European Universities, consultancy companies, public agencies and hydropower industry, encompassing experts in fish biology, river ecology, environmental fluid mechanics and hydraulic engineering. The 15 ESRs will have access to a number of laboratory and field facilities, modelling techniques, experimental practices and instrumental technologies, to expand current understanding of key fundamental fish bio-mechanical, behavioural and physiological processes, and to promote development of novel tools and management solutions in the area of freshwater fish protection.
Project **EUROFLOW** aims to train a new cohort of researchers to be future leaders in the field of applied aquatic science and generate the evidence base for identifying the best ways to manage the quantity, quality and patterns of e-flows to sustain river ecosystems. EUROFLOW Early State Researchers (ESRs) aim to develop new theoretical and empirical insights via ground-breaking experimental manipulations, large-scale field surveys and the development of cutting-edge models to inform the management of water flows and aquatic ecosystems in river basins. These research leaders will undergo advanced training in: (i) river ecosystem science, (ii) transferable scientific and life skills, and (iii) collaborative working with international and inter-sectoral networking. The project aims to progress the field of e-flow science and management intellectually by establishing work on 15 linked projects, catalysing communications amongst 23 institutions (and beyond to their wider networks), as well as enabling continuous intellectual cross-fertilisation.

11.5 Hydropeaking

Hydropeaking may negatively affect the downstream section on the hydro morphology of the river and on aquatic organisms, either directly (mortality by stranding, catastrophic drift, etc.) or indirectly (modification of physical habitat, water quality, etc.). Knowledge on the causes has recently improved: 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 impact. Solutions can be provided through constructive devices (demodulation basin downstream of the plant) or operational restrictions. The latter are very expensive and not compatible with the objective of production flexibility. Moreover, there is still a lack of consensus on the assessment of the 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 in the water body. At business level, new diversion power plants are often not economically viable. Nevertheless, they provide significant positive economic effects at 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's life: design, construction, exploitation, maintenance and dismantling. In particular, it is very difficult to assess medium- or long-term impacts, especially in a 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.

Project **AMBER** aimed at delivering innovative solutions to river fragmentation in Europe by developing more efficient methods of restoring stream connectivity through adaptive barrier management. The project sought to address the complex challenge of river fragmentation through a comprehensive barrier adaptive management process, based on the integration of programme design, management, and monitoring to systematically test assumptions about barrier mitigation, adapt and learn. The project has produced several public reports, including:

- Guidance on Stream Barrier Surveying and Reporting. Part A: Locating, Surveying and Prioritising Mitigation Actions for Stream Barriers
- Country-specific reports containing the metadata
- Classification map of running waters considering fish community structure and barrier impacts
- Conceptual model of ecological impacts of barriers in EU considering fish habitat selection criteria for running waters
- Rapid Barrier Passability and Hydropower Assessment Tool - Guidance Notes
- Rapid Habitat Assessment with Remote Sensing
- Molecular toolkit: taxon-specific set of primers, protocols and pipelines
- Quantification of economic costs and benefits of river infrastructures (evaluation of natural capital)
- River Infrastructure Planning Decision Support Tool
- Review of benefits, challenges, and trade-offs in adaptive barrier management (Best Practice Report)
- Report of Case Studies Demonstrating the Effects of Barrier Removal, Mitigation and Installation
- Role of barriers in managing aquatic invasive species
- Book on Best Guidance on Adaptive Barrier Management in Europe

Project **Lost-Biodiv** aims to analyse the environmental impacts of the ecosystems of so called 'islands' (i.e. habitat loss and fragmentation of ecosystems) created by construction of dams. It will particularly study and evaluate the interactions between species in 35 forest islands and three mainland continuous forest areas in the biggest hydroelectric dam in South America. The research will use available data on vertebrates, invertebrates and plants.

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 lower reservoir while the upper reservoir is located on a high point of 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 to save civil engineering expenses and reduce the onshore footprint, thus limiting the competition for land use;
- the plant is fully fed by seawater, which minimize the hydrology risk and the competition with freshwater use. The plant can even be implemented in arid deserts.

Worldwide site screenings show numerous coastal areas combining high solar and wind resources and a favorable topography, where sea water pumped-storage plants could bring the required flexibility to the system to allow an increased penetration of variable renewable energy sources. Opportunities of hybrid energy and desalination schemes are 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 shall 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 shall be fully watertight to prevent saltwater infiltration in soil and groundwater;
- mitigation measures shall be implemented to limit the biofouling growth on the water intake screens, along the waterways and on the turbine, in order to avoid reduced efficiency;
- corrosion protection strategies shall be implemented to prevent the corrosion steel components in contact with seawater;
- civil works shall 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 one high-head sea water pumped-storage plant to have been built and operated in the world. It was located on the northern part of Okinawa Island, in Japan. The main characteristics of the plant are summarized in Table 1.

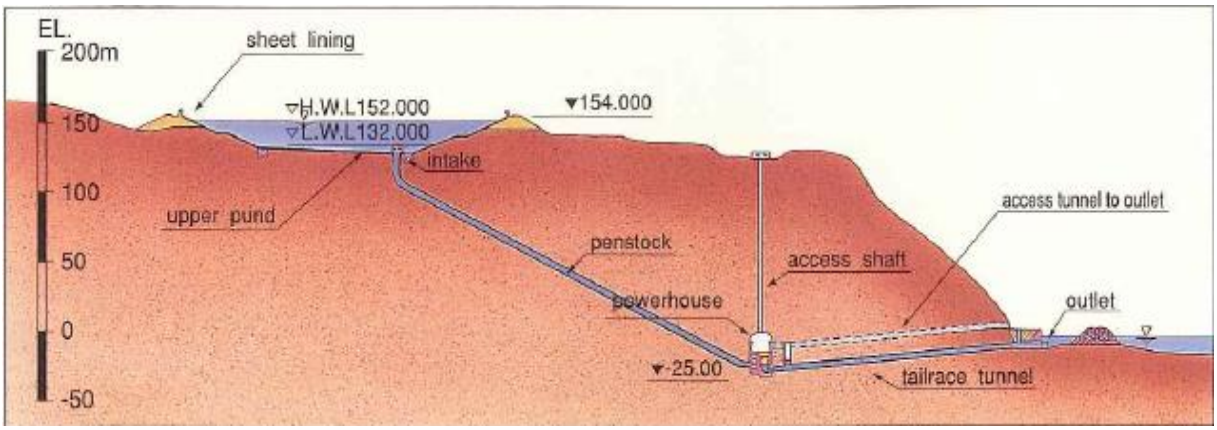

Figure 12-1: Okinawa Yambaru sea water pumped-storage plant. General view of the site and profile of waterways

Installed power	*30 MW*
Effective head	*136 m*
Maximum discharge	*26 m^3/s*
Upper reservoir effective storage capacity	*0,56 $10^6 m^3$*

Table 12-1 : Main characteristics of Okinawa Yambaru Sea Water Pumped Storage Plant

Figure 12-2 - Okinawa Yambaru sea water pumped-storage plant

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 “Espejo de Tarapaca” project in Atacama Desert in Chile (300 MW) or Cultana Pumped-Hydro project in Australia (220 MW).

The technology readiness level of Seawater Pumped Storage Plant is deemed to be 8-9.

12.2 Tidal range power plant

12.2.1 Concept

A Tidal Range Power Plant consists of a dam enclosing a sea area with high tidal ranges, sluices gates and low head turbines. The sluice gates are used to control the level inside the reservoir, 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 in a straight line, such as La Rance power plant operated by EDF (France).
- A “coastal tidal lagoon” encloses an area of coastline behind a breakwater, such as Swansea Bay Tidal Lagoon in development in UK.

- An “offshore tidal lagoon” encloses an isolated area 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 “Tidal Garden”.

Figure 12-3: La Rance Tidal Power Plant (France, 240 MW)

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

- **one-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 sufficiently low levels, the turbine gate is opened and the water from the reservoir channeled into the turbine.
  - **flood generation**: While the tide is rising the water flows through the 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 at 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 12.2.3).

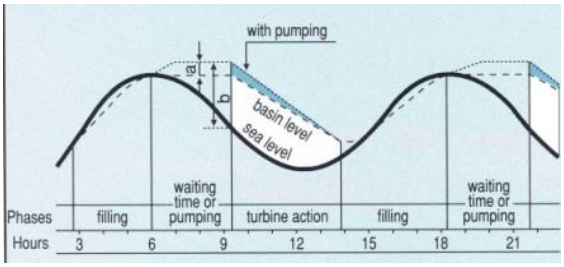

Figure 12-4 - One-directional operation (ebb)

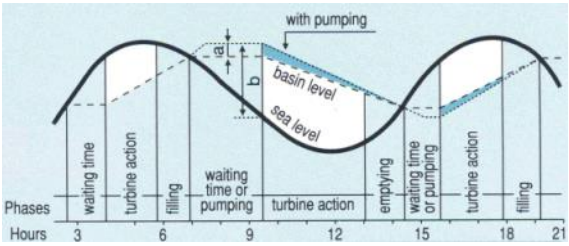

Figure 12-5 – Bi-directional operation

The tidal range energy has the advantage that is very predictable, since ocean tides can be foreseen with extreme precision. Moreover, tidal power plant’s infrastructures 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 flooding 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);
- the 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.);
- the social integration: the project shall mandatorily co-constructed with the local stakeholders as a territory project.

12.2.3 Technological Readiness Level

Five industrial scale Tidal Power Plants are currently in operation in the world, as shown in figure 12-6. La Rance power plant has been operated by EDF for more than 50 years and still generates around 0.5 TWh/year.

Figure 12-6: Tidal Power Plants in the world

After decades without any tidal range project in Europe, a new momentum has been observed in the UK with the development of coastal lagoons projects, among which we find the iconic Swansea Bay Tidal Lagoon. However, the business profitability of these projects is still weak in 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.

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

Project **PowerKite** aimed to design, build and deploy a power take-off system (PTO) for novel tidal energy collector concept, the Deep Green subsea tidal kite. The overall objective of the PowerKite project was to gather experience in open sea conditions to enhance the structural and power performance of the PTO for a next generation tidal energy converter to ensure high survivability, reliability and performance, low environmental impact and competitive cost of energy in the (future) commercial phases. The core innovation of the project resides in the electro-mechanical

design of the PTO, allowing the array to be deployed in sites with low velocity currents. The project aimed to develop full-scale components of the turbine, generator, seabed power electronics, array transformer and subsea export cable, as well as develop a new material for the mooring system (tether) combining the required buoyancy (to avoid the seafloor and the surface) with the appropriate modulus, strength and fatigue properties (to hold an oscillating load of 200 tons). The project´s innovative technology was to double the tidal power market potential, decrease the cost of energy with up to 60% and decrease the weight per installed MW at least 20 times compared to other tidal energy converters. The project has produced several public reports, including:

- Environmental Monitoring Baseline Report
- Collection of Environmental Data Report
- Commercial Power System Design Report
- Commercial Service and Maintenance Strategy Report
- LCA Report
- Environmental Impact Report
- Industrial Value Chain Report
- Certification and Standardization Report

12.3 Referenced HORIZON 2020 Projects

GA ID	Funding scheme	Acronym	Name	Website	Duration
727830	RIA – Research and Innovation Action	FIThydro	Fishfirendly Innovative Technologies for Hydropower	www.fithydro.eu	Nov 2016 – Apr 2021
764011	RIA – Research and Innovation Action	HydroFlex	Increasing the value of Hydropower through increased Flexibilty	www.h2020hydroflex.eu	May 2018 – Apr 2022
873765	SME Instrument phase 2	Turbulent	A revolutionary HYDRO POWER technology to sustainably exploit super-low-head water steps	turbulent.be	Aug 2019 – Jul 2021
641811	RIA – Research and Innovation Action	IMPREX	IMproving PRedictions and management of hydrological EXtremes	imprex.eu	Oct 2015 – Sept 2019
676629	RIA – Research and Innovation Action	EoCoE	Energy oriented Centre of Excellence for computer applications	www.eocoe.eu	Oct 2015 – Sept 2018
748969	MSCA – Individual fellowship	SHYDRO-ALP	Quantifying ecological effects of small hydropower in Alpine stream ecosystems	n/a	May 2017 – Apr 2019
870504	IA – Innovation Action	HYPOS	HYdro-POwer-Suite	hypos-project.eu	Dec 2019 – May 2022
832269	SME Instrument phase 1	HYDROGO	Energy from water in motion: efficient, customisable off-grid hydro-electricity for rural areas with stream access	Deepriveras.com	Nov 2018 – Feb 2019
772867	SME Instrument phase 1	RIVER-POWER	Water flow kinetics energy exploitation for mini/micro hydropower plants	n/a	Jun 2017 – Oct 2017
690268	RIA – Research and Innovation Action	DAFNE	Use of a Decision-Analytic Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast growing developing countries.	dafne.ethz.ch	Sep 2016 – Oct 2020
857832	IA – Innovation Action	XFLEX HYDRO	Hydropower Extending Power System Flexibility	xflexhydro.net	Sep 2019 – Aug 2023

689682	RIA – Research and Innovation Action	AMBER	Adaptive Management of Barriers in European Rivers	amber.international	Jun 2016 – Sep 2020
690857	MSCA – Research and Innovation Staff Exchange (RISE)	KEEPFISH	Knowledge Exchange for Efficient Passage of Fishes in the Southern Hemisphere	keepfish	Jan 2016 – Dec 2019
792678	MSCA – Individual fellowship	Lost-Biodiv	Predicting changes in species interactions following species loss in hydroelectric reservoir islands	n/a	Dec 2019 – Nov 2021
807109	SME Instrument phase 1	HyKinetics	An innovative axial turbine for conversion of hydro-kinetics energy to electricity for river applications	n/a	Feb 2018 – Jul 2018
778602	SME Instrument phase 2	ECO-DRILLING	Environmentally efficient full profile drilling solution	norhard.no/eco-drilling	Sep 2017 – Feb 2020
776868	RIA – Research and Innovation Action	SECLI-FIRM	The Added Value of Seasonal Climate Forecasts for Integrated Risk Management Decisions	http://www.secli-firm.eu/	Feb 2018 – Oct 2021
867843	SME Instrument phase 1	Waterjade	Waterjade: the global platform to predict water resources	http://www.waterjade.com/en/	Jun 2019 – Nov 2019
883553	RIA – Research and Innovation Action	ALPHEUS	Augmenting grid stability through Low-head Pumped Hydro Energy Utilization & Storage	https://alpheus-h2020.eu/alpheus-introduction/	Apr 2020 – Mar 2024
860800	MSCA – European training networks	RIBES	RIver flow regulation, fish BEhaviour and Status	https://www.msca-ribes.eu/	Jan 2020 – Dec 2023
811624	SME Instrument phase 1	SMART Slowflow	Kinetic Micro Hydro System for electrification of rural areas.	https://www.smart-hydro.de/	Jun 2018 – Nov 2018
814958	RIA – Research and Innovation Action	AFC4Hydro	Active Flow Control system FOR improving HYDRaulic turbine performances at off-design Operation	https://afc4hydro.eu/	Jun 2019 – May 2023

773606	SME Instrument phase 1	WATEC	Development of a novel wave tidal energy converter (WATEC) to lower renewable electricity generation costs	https://pliosaurenergy.com/	May 2017 – Sep 2017
654444	RIA – Research and Innovation Action	OPERA	Open Sea Operating Experience to Reduce Wave Energy Cost	http://opera-h2020.eu/	Feb 2016 – Jul 2019
765553	MSCA – European training networks	EUROFLOW	A EUROpean training and research network for environmental FLOW management in river basins	https://water.leeds.ac.uk/our-missions/mission-4/euroflow/	Sep 2017 – Aug 2021
641739	RIA – Research and Innovation Action	BINGO	Bringing INnovation to onGOing water management – A better future under climate change	http://www.projectbingo.eu/	Jul 2015 – Sep 2019
654438	RIA – Research and Innovation Action	PowerKite	Power Take-Off System for a Subsea Tidal Kite	https://www.powerkite-project.eu/	Jan 2016 – Dec 2018
766499	SME Instrument phase 2	DP Renewables	A range of economically viable, innovative and proven HydroKinetic turbines that will enable users to exploit the huge potential of clean, predictable energy in the world's rivers, canals and estuarie	https://designprorenewables.com/	Jul 2017 – Mar 2020
698201	SME Instrument phase 2	Hydrolowhead	Profitable Low Head Hydropower	http://hydrolowhead.com/	Nov 2015 – Oct 2017

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