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Chapter

Innovative Projects and Technology Implementation in the Hydropower Sector

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Abstract

In this chapter, some innovative case studies in the hydropower sector are discussed, highlighting how novel technologies and operational practices can make it more efficient, sustainable and cost-effective. Some practices to reduce hydropeaking effects, improving fish habitat, and turbines with higher survival rate, allowing to bring fish survival >98%, are discussed. The retrofitting of non-powered barriers can help to minimize the environmental impacts, reducing costs by more than 20%. New turbines are described focusing on their advantages with respect to standard ones, in particular, water wheels in irrigation canals to promote the valorization of watermills and old weirs, the very low head (VLH) turbine in navigation locks (reducing overall cost by more than 20%), the vortex turbine, and the Deriaz turbine with adjustable runner blades to improve the efficiency curve, especially at part load. Digitalization can help in preventing damages and failures increasing the overall efficiency and energy generation by more than 1%.

Keywords: aqueduct, Deriaz, digitalization, fish, hydropeaking, retrofitting, turbine, sustainability, VLH, water wheel

1. Introduction

Hydropower is the largest renewable energy source used worldwide, with 1308 GW of global installed capacity in 2019. The benefits of large hydropower plants (>10 MW) with a reservoir are related to the multipurpose use of the reservoir, e.g. energy generation, job opportunities, better water management, storage capacity, and stabilization of the electric grid thanks to the flexible operation, while small hydropower (SH, <10 MW) typically contributes to local development, decentralized energy generation and market opportunities in remote areas [1, 7].

The hydropower sector is undergoing a technological evolution, due to the new needs it has to deal with. Hydropower is required to be more flexible, as the integration of wind and solar energy sources in the electric grid (characterized by an intermittent and highly variable production) are increasing the variability of the electricity market [1]. Furthermore, hydropower is required to be more environment friendly, as the interruption of the longitudinal continuity of a river and the related fragmentation generated by a dam generate severe environmental impacts that should be properly addressed [2–4]. Hydropower is also required to become cheaper, with a lower investment cost, so that the reuse of existing structures and the repowering of non-powered dams are perceived as a suitable option to reduce hydropower cost while avoiding additional river fragmentation [5].

Therefore, several emerging technologies and best practices are under development [6, 7] aimed at increasing hydropower flexibility, cost-effectiveness and sustainability, minimizing environmental impacts, and providing sustenance and electrification to rural areas [8]. More flexible turbines are being developed to cope with the always more frequent grid instabilities and load variations [9], pumped storage hydropower plants to allow storage capacity and flexibility [10], digitalization to prevent failures and to optimize the operation [6, 7], new low head hydropower converters to be used in irrigation canals and at low head existing barriers [11, 12], and more fish-friendly solutions to reduce impacts on fish [13].

In this chapter, some innovative case studies from Italy, USA, Belgium and Switzerland are discussed to show recent innovations in the hydropower sector. In particular, the discussed case studies are related to the following topics:

- Hydropeaking reduction
- Ecologically improved turbines
    a. Reaction turbines
    b. The vortex turbine
- Reuse of existing barriers:
    a. Waterways and basins
    b. Aqueducts
    c. Overflow from dams
    d. Weirs in irrigation canals
    e. Navigation locks
- New turbines: the Deriaz turbine
- Digitalization

These case studies are described with the aim of showing how the implementation of novel methodologies and technologies can help in reducing costs and impacts while increasing efficiency and energy generation. Proper references are included for the readers interested in knowing more about the technical details of these technologies, while here we will mostly focus on their benefits and effects.

2. Hydropeaking reduction

Hydropeaking refers to frequent, rapid, and short-term fluctuations in water flow and water levels downstream and upstream of hydropower stations. Such fluctuations are becoming increasingly common worldwide due to the variable electricity market and are known to have far-reaching effects on riverine vegetation

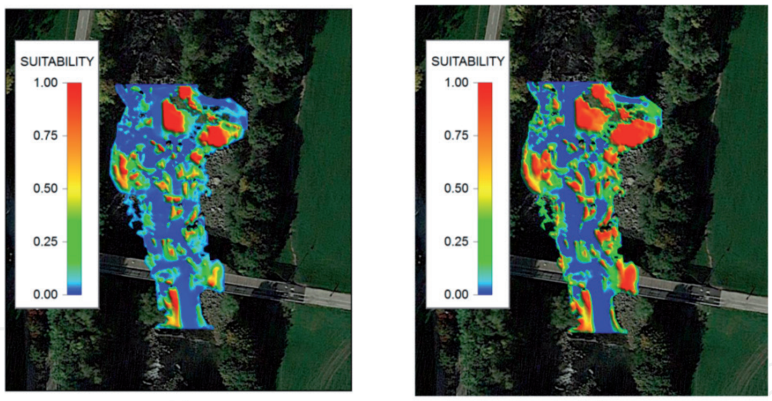


Figure 1.
(a) Suitability distribution for adult Salmo marmoratus and (b) young S. marmoratus. Q = 4.0 m³/s [7].

and fish communities. The modified hydrology caused by hydropeaking has no natural correspondence in freshwater systems, and few species can adaptat [14]. Hydropeaking can be compared to artificial floods that drastically worsen the quality of the river environment [15].

In this context, the Sant Antonio hydroelectric plant was built in 1952 on the Talavera River in Bolzano, Italy. To mitigate the hydropeaking, the construction of two large demodulation reservoirs was chosen to store the water released from the turbines. The use of reservoirs is indeed considered one of the most effective methods to reduce hydropeaking [16]. The reservoirs gradually fill up when the turbines are operating and slowly empty when the plant works at part load.

Downstream of the plant the ratio between the maximum and minimum flow rate has been reduced from 1:15 to a value of 1:4. The ecological effects of the demodulation reservoir were estimated by examining water depth and flow velocity [17], depending on fish preferences and focusing on *Salmo marmoratus* and *Thymallus thymallus* (**Figure 1**).

The weighted usable habitat area (WUA) [18] was calculated to show how the underground demodulation reservoir improves the habitat availability both in the conditions of minimum release (WUA_{min}, occurring when the demodulation reservoir releases water) and in the maximum release conditions (WUA_{max}, when the peak flow rates are flattened).

The analysis of the expected effects on an annual basis shows for adult *Thymallus thymallus* an increase of 67.5% in WUA_{min} and a reduction of 1.2% in WUA_{max}, and for young *Thymallus thymallus* an increase of 23.4% in WUA_{min} and 6.3% in WUA_{max}. For adult *S. marmoratus,* it was estimated an increase of 14.6% in WUA_{min} and 2.9% in WUA_{max}, and for young *S. marmoratus* an increase of 3.4% in WUA_{min} and 7.5% in WUA_{max}.

3. Ecologically improved turbines

3.1 Reaction turbines

Ecologically improved turbines have gained attention in the past two decades and are designed with a strong focus on reducing the hydraulic stressors leading to mortal injury of migrating fish. A review work [13] on the first generation of "fish-friendly" turbines described the conceptual development and implementation of two relevant technologies designed for better fish passage conditions, namely the minimum gap runner (MGR) and the Alden turbine. Such technologies are continuously improving to give rise to a second generation of "fish-friendly" turbines that yield greater improvements in fish survival than the first generation (reducing blade-strike effects) and that accommodate a larger biodiversity of fish present in the migratory corridor. The pressure-related effects are important when there is a greater biodiversity since most migratory fish are prone to mortality due to barotrauma effects caused by the rapid decompression.

The Alden turbine has three blades wrapped around the shaft and it is the evolution of the Francis turbine. The Alden turbine rotates slower compared to conventional Francis turbines. Presently, the unit is only applicable for small-scale hydropower. Instead, the recent development of the Kaplan turbine is the minimum gap runner (MGR), the DIVE, and the very low head (VLH) turbine. Studies with such turbines report improved survival rates compared to the conventional design. The design of the minimum gap runner (MGR) reduces the gaps between the adjustable runner blade and the hub as well as between the blades and the discharge ring. In the DIVE turbines, the double regulation is provided by the variable rotational speed instead of the adjustable runner blade pitch. Such an approach allows maintaining the blades always in their maximum opening position reducing the strike probability with fish and avoiding dangerous gaps between the blades and other parts of the machine. The very low head (VLH) is adapted to sites below 5 m head, with fixed runner blades and adjustable rotational speed.

The U.S. Army Corps of Engineers (USACE) Ice Harbor Lock and Dam (**Figure 2**), located in Washington State, is one such facility focused on improvement under this point of view. The dam houses six large vertical Kaplan turbines. Units 1–3 produce 107 MW at 27.1 m of net head and were commissioned in 1961. Units 4–6 produce 130 MW.

The turbine runners and associated water passageway modifications were investigated with computational fluid dynamics to assess various fish passage criteria, including reducing shear stresses and a target minimum nadir pressure within the water passageway of atmospheric pressure, 101 kPa [19].

During the test procedure, 1068 treatment fish were released and 1030 were recaptured. At the peak efficiency condition, the 48-h survival estimates, excluding predation, were 98.16 ± 0.84%. A total of 15 of the recaptured treatment fish (1.5%) underwent visible injuries, in particular bruising to the head and body (0.7%) and eye damage (0.5%). Four fish (0.4%) were decapitated. Survival at 48 h at the peak efficiency was 2.2–3.3% higher for the new Unit 2 than at the existing adjustable blade runner tested in 2007 (Unit 3). About 1.5% of fish were injured at Unit 2, while 3.8% at Unit 3. About 0.4% of fish were decapitated at Unit 2, less than at Unit

Figure 2.
Ice Harbor Lock and Dam, located on the Snake River in southeast Washington State, USA [7].

3 (1.2%). It was also found that the target minimum nadir pressure of 101 kPa and the blade strike reduction were satisfied.

3.2 The vortex turbine

Hydraulic turbines with a free surface operation are generally considered fish-friendly, due to their large flow passages, no high-pressure gradient and no pressurized flows, and low rotational speeds [11, 29]. This is the case of the gravitational vortex turbine [7, 11].

The vortex turbine can operate within a head ranging from 1 to 4.5 m and with flow rates from 0.7 to 9 m^3/s. The current section describes the rehabilitation of a vortex turbine installed on the Ayung River in Bali. The head is 1.85 m and the flow is 1.5 m^3/s. The previous turbine was limited to 5 kW due to technical problems with the generator. The rotor often got blocked by debris, and, after a flood, the drivetrain underwent irreparable damages. The new runner has a diameter of 1.2 m and the concrete basin diameter is 3.9 m, where there is the vortical flow that drives the runner. The rotational speed is 96 rpm, with a generated power of 13 kW and thus with a global efficiency of 55.8%. Numerical simulations predicted good ecological behavior in relation to fish passages. The equivalent maximum acclimation pressure was P_a = 17.19 psa, while the minimum exposure pressure was P_e = −1.1 × 104 Pa (relative) = 13.1 psa, leading to P_e/P_a = 76%, above the threshold limit (60%). Furthermore, the maximum pressure drop rate is below 116 psi/s, which is below 500 psi/s, the threshold limit. There were also additional benefits of using this turbine, as the smaller dimensions and a lightweight turbine (rotor and drive train weight is 550 kg), and the relatively low cost (0.07 EUR/kWh including maintenance). Obviously, the civil structure of the concrete circular basin has to be considered, and future studies should aim at minimizing its dimensions.

4. Reuse of existing barriers

The powering of non-powered dams–NPDs—and the exploitation of existing barriers is one of the developing hydropower practices aimed at avoiding new interruptions of the longitudinal river connectivity [5]. For example, in USA there are 2500 dams that provide 78 gigawatts (GW) of conventional hydropower and 22 GW of pumped storage hydropower, but the United States has more than 80,000 NPDs, providing a variety of services ranging from water supply to inland navigation. Powering of these dams can add 12 GW, 8 GW of these from 100 dams [20]. Instead, a feasibility study conducted in the Piedmont region of North Carolina, cataloging over 1000 non-Federal dams with hydraulic heads ranging from 4.6 m to 10.7 and power capacity <300 kW, showed that most of the dams were not financially convenient for hydropower applications, although some low head dams may be exploited for hydropower applications if adequate funding opportunities were provided as for wind and solar markets [21]. In Europe, the main advantage of this approach is that most of the infrastructures are already in place and the requirements in the capital are between 30 and 50% of that for mini-hydro stations constructed from scratch. According to the European Environment Agency (EEA), there are currently approximately 7000 large dams in Europe and thousands of additional smaller dams. Thus, it is expected that a power potential exists in European NPDs. In South Africa, the potential of NPDs is estimated at 250 MW [22]. It is estimated that in Europe there are 65,000 small barriers, for example historic weirs and mill sites [23].

4.1 Waterways and basins

In this section, two historic channels, that provided water for irrigation to Modena and Reggio Emilia fed by a reservoir of 800,000 m^3, are examined (**Figure 3**). These channels are no longer feedable due to the lowering of the river bed. They are located in San Michele dei Mucchietti on the Secchia River, Sassuolo (MO, Italy), and Castellarano (RE, Italy). The water supplies are managed by legally different subjects with leading management in charge of Consorzio di Bonifica Emilia Centrale. The central part of the dam is made of a concrete body with a surface spillway and two bottom sluice gates; the right and left shoulders are made of earth.

Although the structure was not conceived to host a hydropower plant (HPP), a hydropower plant was successively designed to use the water-level difference generated by the weir without water resource subtraction to the riverbed. The main characteristics of the plant are average flow rate: 10.54 m^3/s, maximum flow rate: 26 m^3/s, gross head: 9.66 m, and nominal concession power: 998.20 kW.

Two vertical axis Kaplan turbines were installed to provide a maximum power of 1207 and 603 kW, connected to two synchronous generators with nominal power equal to 1476 and 800 kVA.

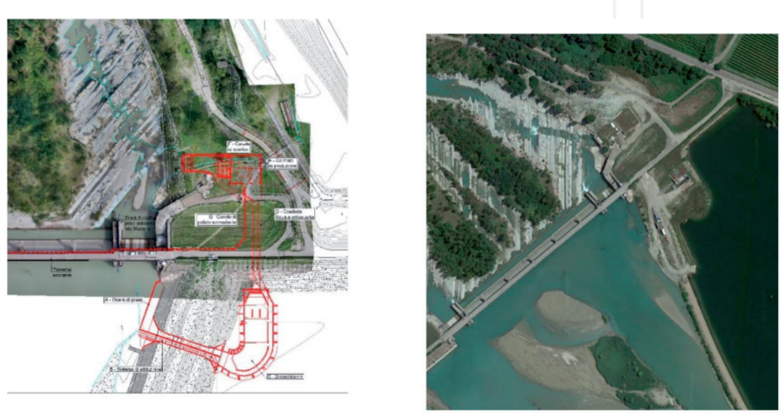
The plant was built by reusing part of the existing infrastructures, in particular:

1. Double connection pipes between the lateral basin and the river, which were originally oversized and used to allow the water to get back into the river from the lateral reservoir. This was done by separating one of the two pipes to separate the flows. 300,000 € were saved thanks to this design choice, because the bank-cutting operation of the lateral reservoir, and the restoration of the waterproof structure was avoided. The inlet front was covered by a concrete sill with the function of both stopping the hydropower intake to ensure the minimum level necessary for the irrigation and protecting from the silting of the intake.

2. The existing accesses were maintained, avoiding the construction of expensive new roads and trails.

3. The embankment of the lateral reservoir was maintained, saving 200,000 € for the construction of protection screens, huge stone boulders, walls higher than the two-hundred-year period flood level.

Therefore, 277 €/kW was the total saving that, compared to an average installation cost of 1300–8000 USD$/kW [24], is a cost reduction of 4.2–25%.



(a) (b)

Figure 3.
(a) Layout of the plant as in the design; (b) aerial photo of the site as built [7].

4.2 Aqueducts

In existing water supply and irrigation networks, there is a hidden hydropower potential that can be exploited. For example, 4 bars are usually required in drinking water networks and 3–10 bars in irrigation plants equipped with sprinklers. If the hydrostatic pressure is higher than the above-mentioned requested operational pressure, the excess pressure can be exploited for hydropower production.

There are several benefits of implementing hydropower systems in existing pipelines: (i) head, pressure, and flow rate are continuously monitored, thus also the power generated; (ii) the placement of turbine can extend the life of nearby pressure reduction valves (PRV) as it reduces the workload of the PRV; and (iii) existing infrastructures are used; thus, some plants may be exempted from licensing, or the cost for permitting may be relatively small, and environmental impacts are reduced. However, as the water demand is not constant, the flow rate in pipelines varies substantially (±50%). Therefore, it is important to understand how turbines behave when subjected to these variations [25].

The Solcano HPP is located in the province of Pescara (Abruzzo region, central Italy) in the municipality of San Valentino in Abruzzo Citeriore. The nominal diameter 300 mm PN40 (40 bar) steel pipe feeds several municipalities with a maximum flow rate Q_{max} = 0.185 m^3/s.

The flow rate in the network varies substantially [26]. A Francis turbine was chosen and designed at Q = 0.125 m^3/s and N = 3000 rpm as design speed [27], but the wide head range made necessary a variable speed system. The installed power was 150 kW. This choice was justified by the fact that a faster synchronous speed was not possible, while a lower synchronous speed was not suitable for Francis turbines. Furthermore, multi-stage Francis turbines increase the complexity of the system and reduce reliability.

A fixed speed Francis solution would exhibit a very narrow operating range with respect to site operating range. Therefore, the variable speed solution, in this case, was selected, varying between 2500 and 4000 rpm.

4.3 Overflow from dams

In reservoir hydropower plants, the discharge necessary to preserve the river ecosystem and that has to be continuosly released downstream, called environmental flow, could be used to produce green energy without any other type of pollution. A case of energy recovery from environmental flow was realized in a mini-hydropower plant located in the North of Italy, in the alpine area of Predazzo close to Bellamonte, in the downstream part of Forte Buso dam. The main features of the Forte Buso plant are dam height 105 m, maximum retention height 99 m, basin storage volume 29.4 Mm^3, total head in maximum basin level 114 m (total head for the turbine set at level 0), and total head in minimum basin level 51 m.

The catchment hydrological basin is 60 km^2. Along the downstream Travignolo river, the following values of environmental flow must be released:

- December–March (winter): 392 l/s.
- April–July (spring) and October–November (autumn): 549 l/s.
- August–September (summer): 470.5 l/s.

The mini-hydropower uses the environmental flow. A permanent magnet generator (PMG) was chosen to face with the large head variation, and the turbine rotational speed varied from 500 to 600 rpm. The Pelton turbine is with a vertical axis and an installed power capacity of 580 kW, with six jets. The PMG designed power is 600 kW and 50 Hz. The plant includes a bypass system that works also in case of electricity failure, to always ensure the correct release of environmental flow. The annual energy generation is 3100 MWh, with an overall efficiency of 92.7%, higher than that of a traditional system (84–86%).

The overall cost was 3,000,000 €, of which 2,086,000 € was the cost of the execution of the plant. Therefore, the unitary cost was 5000 €/kW of installed power. The payback time is 6 years for the return of the investment. If two turbines would have been used, the cost would have been increased by 60%, while management and maintenance charges almost doubled. The payback time would have been increased to 9 years.

4.4 Weirs in irrigation canals and in old mills

In rivers, irrigation canals, and at old mill sites, there is a hydropower potential with very low head differences below 2.5 m. The power mostly ranges from 5 to 100 kW. Much of this potential is unused since modern hydropower technology is not cost-effective for such a very low head/high flow rate situation [28]. It is estimated that in Europe there are 65,000 unused historic hydropower sites, out of which 27,000 are old water mills that could be repowered by using water wheels [23].

Water wheels have been recently discovered to be efficient and cost-effective hydropower converters in this context, so that, in the last decade, the horizontal axis water wheel has been again reintroduced in the market for electricity generation. This was due to the hydraulic efficiencies of more than 70%, coupled with the low costs compared with other low head turbines [11] and high ecological behavior in relation to downstream migrating fish [29].

Horizontal axis wheels can be classified into gravity type and stream type. Gravity wheels mainly use the potential energy of water, that is, the water weight [12], and can be classified into overshot [30], breastshot [31], and undershot wheels [28] depending on head and flow rate, while stream water wheels use the kinetic energy of a water stream [32].

In this section, a breastshot water wheel realized in North Italy is presented. Breastshot water wheels are generally used below 4 m head and flows per meter width typically below 800 l/s. The water inflow is near the rotation axis.

Figure 4 depicts the water wheel installed in an irrigation canal in North Italy. The head difference is 1.85 m with a flow rate of 1.0 m^3/s. The wheel is made of

Figure 4.
Water wheel installed in an irrigation canal in North Italy.

COR-TEN steel. The wheel diameter is 3.6 m, for a wheel width of 1.35 m and 30 blades, supported by a shroud in the canal bed 2 m × 6 m. The global efficiency of the wheel and the power take-off (generator and gearbox) is estimated to be 0.67. The electric generator is a synchronous one, with 4 poles and 95.5 Nm of torque. Its efficiency is 0.95, as also the efficiency of the gearbox and of the inverter. The wheel weight is 51 kN, in agreement with the equation proposed in [33].

4.5 Navigation locks

Navigation locks present a perfect example of existing facilities where hydro turbines, instead of the gates, could regulate the flow, producing energy otherwise wasted. The very low head (VLH) machine is a promising technology in this context [7]. In this section, two VLH installations are described.

The first plant is located in the Canda locality (Rovigo, Italy) on the Canal Bianco, and it was commissioned at the end of 2016. The canal height is 7 m, canal width 9.5 m, gross head 3 m, and the mean annual flow 16.5 m^3/s. The second plant is located in Bussari (Rovigo, Italy), again on the Canal Bianco, and it was commissioned in the first half of 2017. The canal height is 6.3 m, canal width 8 m, gross head 2.56 m, and mean annual flow 25 m^3/s.

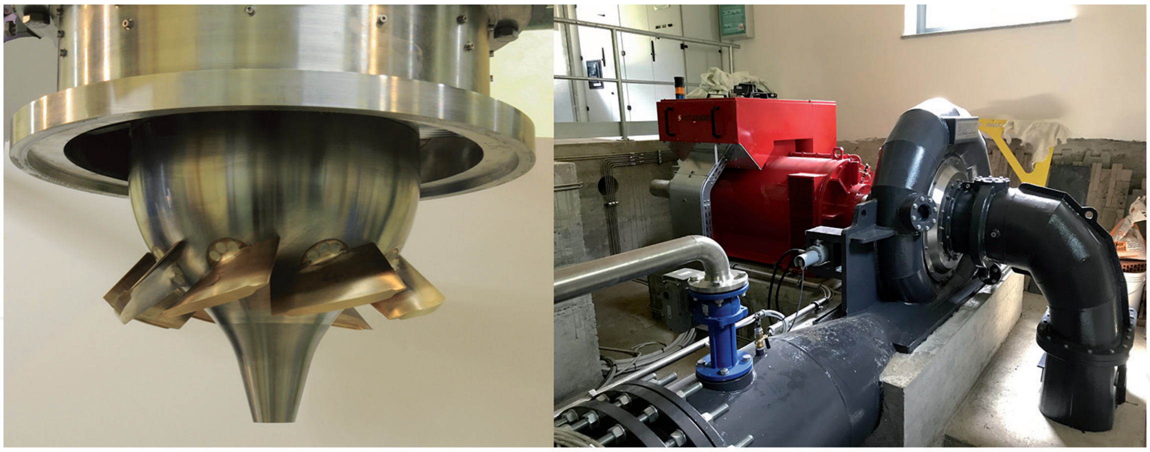
In the Canda power plant, two VLH 3150 (runner diameter of 3150 mm) were installed with a total power of 2 × 256 kW achieving an annual production of 2,888,000 kWh. In Bussari, one VLH 5000 (runner diameter of 5000 mm) was installed with a total power of 481 kW and annual production of 2,751,000 kWh.

Comparing this solution similar projects with Kaplan turbines, the civil costs were reduced by 80%, while the design of an *ad hoc* steel structure instead of a standard one lead to an increase of 40% of mechanical structures. Therefore, the total cost of the Canda and Bussari projects was 3950 and 3650 €/kW, respectively, lower than the typical cost of similar plants where civil works are needed (5000 €/kW). This means that the cost reduction ranged between 20 and 30%.

5. New turbines: the Deriaz turbine

Nowadays, climate changes, variable flow rates, unpredictable floods, and the frequent instability of the electric grid require new hydropower technologies to provide greater flexibility over an extended range of hydraulic conditions. Improved flexibility means maintaining an optimal efficiency while reducing flow instabilities, especially at off-design conditions, and efficiently respond to grid requirements and instabilities. This is provided by control techniques (1), new and more geometrically-adjustable turbines (2), better governors (3), and integration with other energy technologies (e.g. photovoltaic panels), additional reservoirs, and batteries (4) [6].

With regard to point (2), the Deriaz turbine, as optimization of the Francis turbine, is gathering a lot of attention. The Deriaz turbomachine (DT), presented by engineer Paul Deriaz, was the first diagonal flow pump-turbine to be designed, in 1926, but during the nineteenth century, it has been almost forgotten. The Deriaz turbine exhibits a lower specific speed than a Kaplan turbine, and it works more efficiently at part loads and at higher available head than a Kaplan turbine. Differently from Francis turbines, the Deriaz is provided with adjustable runner blades, providing higher flexibility at variable flow rates and with higher efficiency at part loads. The maximum efficiency is around 90%, and it can be kept constant from 30 to 120% of the design flow rate. The Deriaz turbine is able to work in pumping mode [34]. Kuromatagawa II power station adopted a vertical shaft Deriaz



(a) (b)

Figure 5.
(a) Deriaz turbine (photo courtesy of Mhylab); (b) Deriaz power plant in Italy (photo courtesy of Artingegneria).

pump-turbine in 1963 to deal with a large head variation and to attain high efficiency at part load. The rotational speed of the Deriaz turbine was 333 rpm during pumping mode and 300 rpm in turbine mode from an effective head of 78 m to the minimum operational head of 39 m with a maximum flow rate of 28 m^3/s. The ratio of unit speeds at maximum efficiency during turbine and pump operation is about 1.1, the same as for the Francis-type pump-turbine [34]. Another interesting example is a mini-hydropower plant built in Italy, with the following characteristics: maximum flow rate: 800 l/s, head: 32.5 m, power: 220 kW, 1000 rpm. The cost was 800 k€ (350 k€ of electro-mech. equipment) (**Figure 5**).

Also, the X-Blade turbine is an evolution of the Francis turbine. It can operate in a larger range of flow and heads before inter-blade vortices, inlet cavitation, or draft tube pressure pulsations occur or become critical. The skewed outlet geometry with the relatively small outlet diameter at the crown contributes to the typical low draft tube pressure pulsation level. The X-Blade turbine generates a smaller and less intensive vortex in the draft tube center than other turbine types, requiring a smaller amount of natural air admission through the runner cone.

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6. Digitalization

The collection and processing of real-world data to adjust the actual working conditions of hydropower turbines can provide advanced grid supporting services without compromising reliability and safety. Apart from the improvement of predictive maintenance allowing for the prolongation of the lifetime, reduction of the outage time, and addressing cyber-security risks, rehabilitation and digitalization involve increasing the overall efficiency and, thus, the produced energy [6].

Recent studies have shown the interest in applying data-driven methods to the data collected during the hydropower plant operation or reduced scale model tests to predict fatigue and condition monitoring, as in [35], cavitation erosion in [36], and performances, as presented by [37].

Further information on the meaning and activity involved in the digitalization concept is well described in [6]. It is estimated that a total of 42 TWh could be added to present hydropower energy production by implementing hydropower digitalization. Such an increase could lead to annual operational savings of 5 $ billion and a significant reduction of greenhouse gas emissions. The increase of

42 TWh/y corresponds to 1.3% of the actual global hydro-generation. This is in line with a recent publication, [7] where it was calculated an additional 0.5% in one case, and 1.2% in a second case, of energy generation of two Italian hydropower plants by implementing the digitalization. The cases reported by Hydrogrid reached an efficiency increase between 0.4% and 1% [38].

Furthermore, digitalization will enable to drastically reduce the response time of hydro-units, especially those of reversible pump-turbines. In [39], it is presented the case study of Z'Mutt, a pumped storage hydropower plant equipped with a 5-MW reversible pump-turbine with variable speed technology using a Full-Size Frequency Converter (FSFC). It is showed that by leveraging numerical simulations and scale model test results during transient operations, and implementing an optimization algorithm to select the best operating sequences, the response time of the turbine can be improved. Digitalization will also allow to assess the economic impact of offering additional reserve flexibility, and to prevent failures and damages with the implementation of HPP digital twins. The cost of a predictive system for one unit (development and implementation at HPP) is about 200,000 EUR [40]. An additional increase and optimization could be achieved with the use of software that uses genetic algorithms such as EASY [41]. To improve further the flexibility of hydropower plants, a number of researchers [42] investigated their stability properties by means of transfer functions representing the dynamic behavior of the reservoir, penstock, surge tank, hydro-turbine, and the generator. A novel approach was developed to establish the dynamic model of the hydro-turbine governing system in the transient process.

HydEA is a platform to analyze the behavior of the plant and that elaborates a reference model of the performance characteristics of the generation units. This allows to detect in real time the deviations from the expected values, finding eventual damages. It is also possible to recognize, through the recalculation of the models at fixed intervals, very slow decay of the system performance. The additional algorithm allows to increase the overall plant efficiency by improving the load on the operating turbines. For example, the production of an Italian plant increased by 1.2% on an annual basis.

The Hydro-Clone is a Real-Time Simulation Monitoring System made of a numerical copy of the hydropower plant that reproduces its real-time dynamic behavior, using the boundary conditions measured *in situ* as input [43]. This system allows to continuously diagnose the health of a plant by numerical cloning the major hydraulic and electrical components of the plant, using the SIMSEN software. The comparison between the simulated and measured quantities enables to understand the health state and behavior of the system. The Hydro-Clone system has been operating since 2014 at the La Bâtiaz power plant (200 MW).

7. Discussion and conclusions

The case studies here collected show engineering insights on new technologies and more sustainable methodologies. These case studies confirm the fact that hydropower is a sector in continuous development. New technologies and methodologies are being implemented to improve flexibility and efficiency and to reduce environmental impacts. **Table 1** summarizes some key results.

New ecologically improved turbines are under development to reduce fish mortality and improve habitat, but more studies should be devoted to the better understanding of the interaction between fish and hydraulic structures. The Sant' Antonio hydroelectric plant uses two large underground demodulation reservoirs to reduce the effects of hydropeaking downstream of the plant, but more work is needed to better determine habitat preferences of some fish species [17].

Case study	Type of improvement	Improvement value
Hydropeaking reduction in Sant'Antonio plant	Fish habitat (WUA)	+67.5%
Ecologically improved turbine at Ice Harbor Lock and Dam	Increase in fish survival rate	>98%
Vortex turbine for low heads	Smaller runner dimensions and fish-friendly behavior	56% efficiency and pressure drop rate below 116 psi/s < 500 psi/s
Reuse of existing structures in San Michele dei Mucchietti on the Secchia River	Cost reduction	500,000 €, or 277 €/kW of cost reduction
Hydropower in aqueducts	Cost reduction and no environmental impacts	150 kW Francis turbine
Hydropower on environmental flow structures	Cost reduction	Payback time reduction from 9 to 6 years
VLH turbines in navigation locks	Cost reduction	Overall cost reduction up to 30%
Digitalization	Preventing failures and increasing efficiency	Less maintenance and increased efficiency +1%
New turbines: Deriaz turbines and water wheels	Flatter efficiency curve, and valorization of watermills	Higher weighted efficiency due to the double regulation, and energy at low head sites

Table 1.
Key improvements from the case studies.

The hydropower energy recovery from existing hydraulic structures is also an emerging trend. In San Michele dei Mucchietti locality, on the Secchia River, the use of existing structures has allowed saving 500,000 €, corresponding to a cost reduction of 277 €/kW. The energy generation from the ecological flow was also described, with a Pelton turbine with a global efficiency of 92.7%. If this facility would have been built with two standard turbines, the cost would have been increased by 60%. Energy recovery in aqueducts is also a sector in rapid development, and in this chapter, a 150-kW Francis turbine with variable speed was described [44].

The VLH turbine was implemented in a navigation canal in Italy, leading to a total cost between 3950 €/kW and 3650 €/kW, while similar plants in which civil works were needed had a total cost of 5000 €/kW. Compared to Kaplan turbines, the VLH turbine also shows a better ecological behavior, but it exhibits a lower efficiency and can only be applied at heads below 5 m.

Digitalization is an emerging trend, especially when hydropower plants have to be modernized (almost one half of the hydropower fleet was built more than 40 years ago). New tools are under development, allowing to improve annual generation spill reduction, and preventing damages and failures.

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