Exploitation of eco-flow downstream of dams built for drinking water, irrigation and/or other purposes

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Introduction

This paper's few pages make no claim to provide a complete and exhaustive review of the content of its title. More humbly, it seeks to bring to the reader's attention a topic that has received much attention in the recent past and which seems to have gradually disappeared from public discourse, just as small hydropower seems to have disappeared or receives little attention.

Back in 2005 I gave the first presentation in a hydropower conference dealing with the potential exploitation of the ecological (ecological) flow for hydropower energy production. At that time, only a few, peculiar and near-experimental applications on both medium-high and low heads were implemented. Nearly ten years later, thanks to new and more mature technologies available (mainly in the hydroelectric units field) and, no less important, to a clearer and more favourable authorisation and tariffs frame, dozens of plants which use the ecological flow were built in Italy. Most of these plants are low or very low head schemes, exploiting the ecological flow released at existing diversion weirs; Some medium and high head applications will be presented, even though they represent a smaller percentage, because of the greater complication of the scheme. Actually the main technological developments are related to low head hydropower plants.

Furthermore an overview on some ecological flow plants is given in the following chapters, underlining the most critical design and operation issues as well.

Some fundamental remarks will be made about economics and future perspectives of this type of applications.

1 Overview

1.1 General remarks and framework

Table 1 summarises the main features of plants, some of them designed by FROSIO NEXT in recent times, exploiting the ecological flow.

Name of the plant	*River*	*Maximum flow [m³/s]*	*Average flow [m³/s]*	*Gross head [m]*	*Installed capacity [kW]*	*Type of unit*	*Energy [kWh/yr]*
Casnigo Scarico	Serio	1,64	1,64	3,05	40	Kaplan Vertical belt	330.000
Casnigo	Serio	1,58	1,58	5,2	70	Kaplan Vertical belt	570.000
Parre	Serio	3,00	1,89	4,3	98	Kaplan Vertical belt	540.000
Prato Mele	Serio	2,46	1,90	4,7	94	Kaplan Vertical belt	617.000
Fonderia	Brembo	2,45	2,45	3,5	70	Kaplan Vertical belt	595.000
Esine	Oglio	4,50	3,10	4,2	155	Kaplan Vertical PMG	890.000
Capriolo	Oglio	10,00	4,13	5,9	480	Kaplan Vertical PMG	1.700.000
Roggia Vetra	Oglio	10,00	6,54	6,3	600	Kaplan Vertical PMG	2.760.000
Urago	Oglio	12,00	10,21	3,5	350	Kaplan Vertical belt	2.400.000
Carema	Dora Baltea	24,00	16,48	4	770	Kaplan Vertical PMG	4.650.000
Chievo	Adige	56,10	56,10	3,1	1.480	Straflomatrix	12.000.000
Santa Giustina	Noce	2,10	2,10	60-128	2.500	Francis vertical	14.000.000

Name of the plant	*River*	*Maximum flow [m³/s]*	*Average flow [m³/s]*	*Gross head [m]*	*Installed capacity [kW]*	*Type of unit*	*Energy [kWh/yr]*
Mollaro	Noce	2,40	2,40	20-30	700	Francis vertical	4.000.000
Palosco	Oglio	5,880	3,74	5,80	315	Kaplan vertical	1.500.000
Sticchi	Chienti	1,32	1,32	7,5	90	Kaplan Vertical PMG	650.000
Santa Caterina	Adige	40,00	36,45	4,3	1.285	Kaplan bulb	9.660.000
Blufi	Imera	2,57	2,20	42-70	1.015	Francis Vertical	950.000
Ala	Adige	22,30	19,25	2,78	860	VLH	3.400.000
Val Schener	Cismon	1,50	1,16	60,9	720	Francis Horizontal	4.300.000
Forte Buso	Cismon	0,55	0,48	94	489	Pelton vertical	2.950.000
Fontanino	Noce	0,18	0,13	108	180	Pelton vertical	950.000
Badia	Mella	9,00	6,35	3,92	295	Kaplan Bulb belt	1.470.000
Bassana	Mella	15,00	7,80	2,48	305	Kaplan Bulb belt	1.100.000
Calcagna	Mella	15,00	7,52	1,81	212	Kaplan Bulb belt	690.000
Martinoni	Mella	15,00	8,99	3,07	351	Kaplan Bulb belt	1.420.000
Montegiorgio	Tenna	9,00	3,71	14,15	1.038	Kaplan vertical	3.740.000
Turano	Turano	0,100	0,100	49,61	40	Pelton vertical	270.000
Santa Maria Magale	Nera	5,000	5,000	5,63	250	Kaplan Vertical Gearbox	1.410.000
Monte Argento	Nera	2,000	2,000	6,25	110	Syphon	700.000

Table 1 – Main features of some plants exploiting the ecological flow

All those plants exploiting the ecological flow are located at the inlet of existing water diversions, usually done for hydropower purposes - sometimes combined with irrigation and drinking water supply schemes; therefore the design problems connected with the optimisation of the joint operation of the two plants, the main one and the ecological flow one or the interaction between the irrigation/drinking water purposes, must be considered as well.

1.2 Upstream water level regulation

Usually the main diversion is operated by regulating the water level just upstream of the hydroelectric units, therefore the water level at the weir, where the ecological flow plant shall be constructed, varies with the flow rate diverted by the main plant, as well as with the flow rate of the water course. As an ecological flow plant usually has a small power output, the analysis of its technical and economic feasibility must evaluate and compare the cost of installing gates - or replacing the existing ones - for regulating the upstream water level at the weir and of losing a certain fraction (up to some ten percent) of the available head due to water level fluctuations.

1.3 Downstream water level variations

The water level upstream of the weir and of the ecological flow plant fluctuates with the flow rate of the river, so it's highly recommendable to monitor these fluctuations on a sufficiently long period in order to place the turbine at a correct elevation, to correctly estimate the average head actually exploitable by the plant and consequently provide an accurate evaluation of its technical and economic feasibility.

1.4 Limitation of the diverted flow rate

The authorisation requirement of limiting the flow rate of the ecological flow plant (in order not to exceed the maximum value of the concession) may be in contrast with the obligation of letting the main plant divert all the water allowed by its water concession. In fact the new diversion, to be legitimated, must not interfere with the existing one.

As already explained above, the water level at the intake usually varies with the flow rate diverted by the main plant, starting from a fixed water level (called set point) just upstream of the existing hydroelectric unit, so it's not possible to identify one elevation for a fixed device such as a spillway. Moreover, a fixed spillway would imply that, for river flow rates (net of the ecological flow) between the minimum and maximum discharge of the main plant, the new plant would steal water either from the river - by diverting more than the ecological flow - or by the existing plant - by discharging back to the river the flow rate exceeding the ecological flow and therefore belonging to the main plant.

Consequently the limitation of the flow rate diverted by the ecological flow plant usually can't be achieved by fixed devices, but only by a mechanical stop on the regulating system (runner blades or guide vanes) of the new turbine.

A possible alternative to the mechanical stop is installing regulating gates at the beginning of the existing headrace channel, in order to keep the water level constant at the weir and consequently install a fixed device, e.g. a spillway.

1.5 Interaction with fish passages

As most of these plants are built on weirs, they are often placed nearby existing or designed fish passages. Consequently it's important to integrate the design of the structures, so the fish passage won't interfere with the plant operation but, on the contrary, the fishes will be attracted by the ecological flow released at the plant outlet. Moreover the regulation of the upstream water level would be beneficial for the fish passage as well as for the plant operation, which is a good reason for installing the regulating gates mentioned at par. 1.2, especially if the owner is the same for the main plant and for the ecological flow one.

Figure 1 – Casnigo Scarico

1.6 Positioning

Some plants - such as Fonderia, Capriolo and Roggia Vetra - take water from the beginning of the existing headrace channel, so they're located just outside the main river bed, in order to protect them from floods and to reduce the necessary civil works. In the case of Casnigo Valle, instead, the new plant is located on the tailrace channel of the existing plant, with very little civil works to put in place the new hydroelectric unit.

1.7 Reduction of the environmental and visual impact

The hydropower plants - and even more so the ones exploiting the ecological flow released at weirs - are naturally located in the immediate vicinity of the riverbed, that is an environmentally sensitive zone; therefore various techniques have been developed for reducing their impact on the ecosystem and the landscape. With regard to the ecosystem, the impact is limited by their small dimensions and by the absence of water withdrawal in any reach of the water body; the visual impact is reduced either by hiding the plant (submerged solution) or by pleasantly inserting it in the local landscape, for instance covering the external structures with local stone and other materials.

1.8 Choice of the electromechanical equipment and plant layout

Submerged units, allowing for a compact plant layout, are often preferred. If a turbine with single regulation (i.e. semi Kaplan with fixed guide vanes and adjustable runner blades) is employed, a gate is necessary for stopping the water flow. It's normally preferable to put the gate downstream of the turbine, so the waterways and the turbine itself remain filled with water and consequently the plant can be smoothly put back into steady operation. The main features, advantages and disadvantage of the latest technological options are briefly discussed in chap. 3.
Another issue concerning the plant layout is the need to reduce the realisation complications and costs connected to the deep excavations (and the necessary retaining walls, sheet piles or micro piles) within or besides the riverbed and consequently below the water table.

In the end, taking into account these issues and the ones (such as environmental impact reduction) described in the previous paragraphs, the layout of the ecological flow plants should always be as compact as possible, both in plan and in vertical dimension.

2 Case studies

2.1 General remarks

Among the plants presented in the previous table, a few examples of different schemes are described in detail. It's interesting to notice all of these ecological flow plants will have the same owner as the main plant. That's why in some cases - e.g. Casnigo and Carema - the regulating gates (hydraulically operated) mentioned at par. 1.2 will be installed at the beginning of the existing diversion waterways.

2.2 Casnigo Scarico - Casnigo - Parre - Prato Mele - Fonderia

All these plants will have a vertical axis Kaplan turbine coupled by belt drive with an external generator, resulting in a very compact layout. Thanks to this some of them, such as Prato Mele and Casnigo, could be placed on one ends of the existing weirs, in place of the short flushing canal collecting water from the sluice gates or the spillways located just upstream of the existing diversion channels.

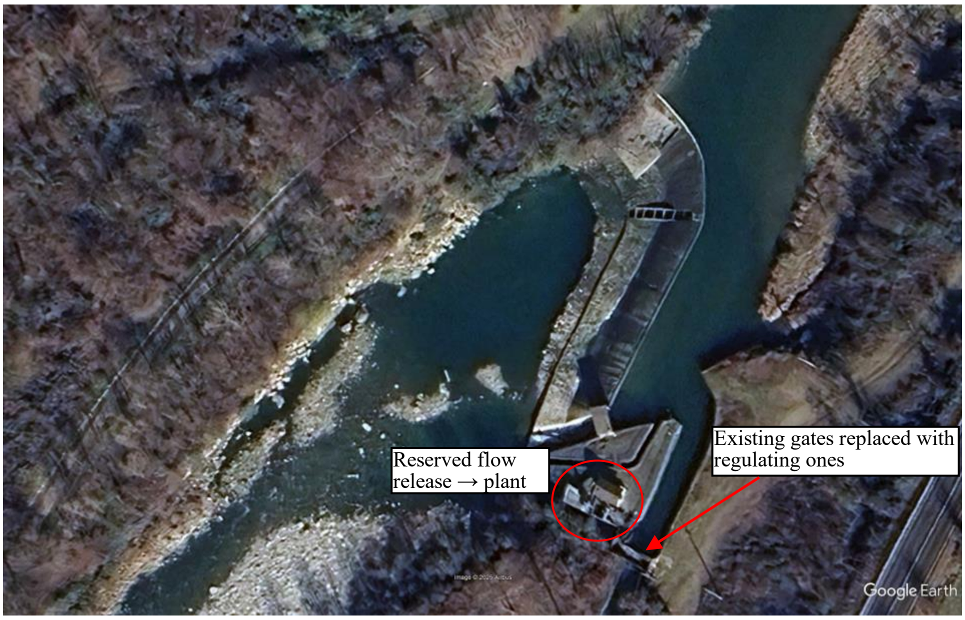

Figure 2 – Casnigo: the on/off gates at the beginning of the headrace channel of the existing plant have been replaced with regulating ones, hydraulically operated

2.3 Capriolo - Roggia Vetra

In both of these plants, located along the Oglio river, downstream of the Iseo Lake, a vertical Kaplan unit has been installed, directly coupled with a submerged permanent magnet generator.

Figure 3 – Roggia Vetra (left) and Capriolo (right) PMG generator

2.4 Chievo

It's a particular case, with a very large flow rate (actually this isn't properly a *mini* hydro plant) and an innovative technical solution, the StrafloMatrix™, that is an array of small propeller turbine-generator units, allowing for compact construction - thanks to the permanent magnet generator with the rotor integrated into the turbine runner - and the possibility to lift and lower the structure (steel module) in a few minutes, just like a gate. The plant has already been operating for nearly five years, since October 2009.

Figure 4 – Ecological flow plant built in the old ship lock at Chievo Dam, on the Adige River, just outside the city of Verona. The headrace channel of the main plant (located in the centre of Verona) is located on the right side of the river.

3 Recent technological developments

3.1 General remarks

The main technological development in the small hydropower sector in the last decades have concerned low and very low head applications. The most important ones are described in the following paragraphs.

3.2 Permanent Magnet Generators (PMGs)

It allows for the direct coupling between turbine and generator with a little encumbrance. Moreover, thanks to the absence of sliding parts, they have a high efficiency (~90% in the design head and flow rate conditions) and they require very little maintenance. These positive features make them a good - although expensive - choice also for small plants as usually are those which exploit the ecological flow.

Among the aforementioned plants, those of Esine, Roggia Vetra, Capriolo and Carema (and also Chievo, with its particular equipment) employ Kaplan units with submerged PMGs, as described in the previous paragraphs.

3.3 Belt Drive

Actually this is an old technology, which has become much more reliable (due to improved belt materials, reinforced with carbon fibres) and has been employed in many recent applications, such as at Casnigo, Prato Mele, Parre and Fonderia. Its advantage is that it allows for a compact layout of the hydroelectric group, without any gearbox. Its disadvantage is that, compared to other technologies, it has a low global efficiency, i.e. no more than 80% in the design head and flow rate conditions.

Anyway, taking into account the requirement of reducing the dimensions - both in plan and in vertical - of the plant, for the reasons explained in chapter 1, the belt drive can often be a sensible choice.

Figure 5 – Belt transmission at Urago plant

3.4 Very Low Head (VLH) Turbines

They are suitable for large flow rates, no less than 10 m^3/s, and of course very low (~1-3 m) heads; therefore they are usually employed only on large rivers. In such cases they may be an alternative to the other types of turbines described in the case studies and listed in the table above.

An important advantage of VLH turbines is that they require very little civil structures: in fact one simply has to fix a steel frame with a runner to the (usually) already existing walls or structures, as shown in the picture below.

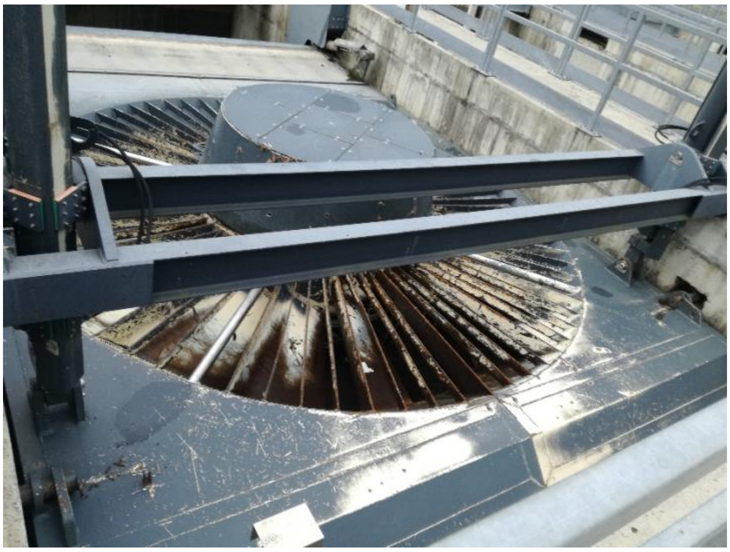

Figure 6 – VLH at Ala plant

3.5 Others

Certainly other types of technical choices - concerning the hydroelectric units and, consequently, the plant layout - are possible for peculiar cases: for instance siphon turbines to be installed over the weir, or cochlea turbines for very low heads (or else the Archimedean screw would become excessively long) and low flow rates.

Figure 7 – siphon unit at Monte Argento plant

4 Authorisations - Tariffs - Economics

4.1 General remarks

The boundary conditions are as much important as the aforesaid technological developments for the expansion of ecological flow exploitation, because the easiness of realisation makes attractive also some plants which otherwise (e.g. if they were normal plants, requiring new diversions) wouldn't be very profitable.

The most important ones are listed in the following paragraphs, with reference to the Italian context.

4.2 Authorisation

The hydropower plants exploiting the ecological flow of existing diversions should have a somehow easier authorisation path, for example, because they should be exempted from the Environmental Impact Assessment.

4.3 Tariffs

Ecological flow plants in Italy are one of the categories which have *priority* access to the incentive system; moreover, for nominal (something like average) capacity under 250 kW - or 500 kW if the owner is a public authority, such as a municipality - they have *direct* access to the incentives, i.e. without passing by the present standard procedure, which implies incentive allocation according to the order and priority of registration into the relevant registers. Another priority factor is to be built on existing (and unmodified by the project) weirs or dams, which is often the case for ecological flow plants.

Therefore these plants, even if they aren't very profitable by themselves, they may prove preferable - compared to larger HP plants - for investors and financiers, due to the somewhat lower incertitude of the path leading to the authorisation, realisation and commitment of the plant.

Finally the following table depicts the technical-economic picture of some of the examined plants.

	Q_{max}	Q_{med}	H_g	P_{turb}	P_{gen}	E	C	C/E	C/P_{turb}	LCOE
	m³/s	*m³/s*	*m*	*kW*	*kW*	*MWh/yr*	*k€*	*k€/MWh*	*k€/kW*	*€/MWh*
Monte Argento	2,000	2,000	6,25	110	106	700	440	0,63	4,00	57
Palosco	5,880	3,74	5,80	315	285	1.500	980	0,65	3,11	67
Urago	12,000	10,21	3,50	400	360	2.400	1.890	0,79	4,73	72
Santa Maria Magale	5,000	5,000	4,29	250	234	1410	1.260	0,89	5,04	77
Carema	24,000	17,22	4,00	870	1.250	4.650	4.400	0,95	5,06	88
Roggia Vetra	11,000	6,54	6,30	600	680	2.760	2.090	0,76	3,48	89
Fonderia	2,450	2,45	3,50	84	90	595	650	1,09	7,74	109
S. Caterina	40,000	36,45	4,50	1.606	1.285	9.660	11.350	1,17	7,07	109
Esine	4,500	3,10	4,20	190	180	890	1.080	1,21	5,68	110
Prato Mele	2,460	1,90	4,70	97	95	617	690	1,12	7,11	111
Capriolo	10,000	4,13	5,90	480	480	1.700	1.870	1,10	3,90	113
Turano	0,100	0,100	49,61	40	37	270	360	1,33	9,00	114
Casnigo	1,580	1,58	5,20	81	77	570	650	1,14	8,02	114
Scarico Casnigo	1,640	1,64	3,05	49	47	330	480	1,45	9,80	149
Parre	3,000	1,89	4,30	95	98	540	880	1,63	9,26	155

Table 2 – Main energy and economic features of some of the plants exploiting the ecological flow

As you can see, the LCOE, which in this represent the minimum price of the energy necessary to make the investment feasible is in many cases rather high so that this type of plants can be reasonably exploited only if some kind of incentives is guaranteed.

5 Future exploitation perspectives

In the light of the ongoing technological development in the Small Hydro field and of the boundary conditions described above, the perspectives for the future exploitation of the ecological flow are mainly focused on low (or very low) head plants built on existing weirs or at the beginning of existing diversion channels, because the other schemes - such as high head plants exploiting the flow released from dams - are more demanding from the financing, authorisation and realisation point of view.

As the rentability of the investment is not often very attractive at the current market prices, as in the past, to be fair, an opportunity to be investigated is that given by the inclusion of these plants within the Renewable Energy Communities (REC). As this type of plants provide an almost constant amount of energy (because the ecological flow is rather constant – at least monthly or seasonally) they can provide an important stabilisation service at REC where a lot of intermittent sources are usually present.

6 Conclusions

The exploitation of the ecological flow downstream of dams and weirs built for drinking water, irrigation and/or other purposes took the advantage in the recent years of some technological advancements, especially referred to low head and very low head plants. Even though globally the technology can be considered mature and most of the sites with reasonable rentability have been already exploited, nevertheless a lot of potential sites worldwide can provide residual hydropower energy and contributing to get decarbonisation targets. A new momentum to the development of new projects can be given by the inclusion of these plants in the Renewable Energy Communities.

The Author

L. L. Papetti, hydraulic and chemical engineer, involved in the design and supervision of hydropower plants since 1990. He is currently Chief Executive Officer and Technical Director of Frosio Next.