Towards the highest efficiency and the lowest environmental impact: a case study showing the recent developments of low head hydropower plants

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Introduction

In the last years research has been focused on the development of hydropower plants exploiting low geodetic heads. This has led to a fast and continuous improvement in the related technology.

By 2020, the 20% of all energy consumption in European Union (EU) member countries must come from renewable sources. As regards hydroelectric power, this objective translates in a significant commitment in developing new capacity and in upgrading of existing facilities throughout Europe.

In our continent the greatest opportunity in this field is related to Small Hydro Power Plants (SHPP). A hydropower plant is usually defined “small” when its rated power is less than 10 MW, even if this definition is not internationally recognized.

Today small hydropower is a renowned technology since it contributes to sustainable development by respecting the environment and allowing decentralized production for the development of remote villages and communities. Implementing SHPPs helps creating a diversified electric system which can provide energy in smaller distribution systems when the main grid is out of service, this improves the reliability of electric energy supply and reduces transmission losses since SHPPs are often located close to their users. Furthermore, on the contrary of conventional hydropower usually equipped with large dams, SHPPs are not an obstacle for migratory fishes.

Industry has developed innovative techniques to minimize potential environmental impacts. In fact, engineers working in the small hydropower field keep on developing specific techniques in order to gain energy efficiency and reduce the environmental impact.

In order to illustrate the development of the traditional low head technology, this article will tell the story of a cascade of nine small- run-of-river hydropower plants. The project consists of three progressive steps of development showing three different configurations of low head hydropower plants.

From tradition to innovation

The River Iskar is the longest river within the territory of the Republic of Bulgaria, which flows entirely within the country’s territory and discharges into the Danube. The nine plants are located along 33 km and their sites have similar characteristics as regards geological and morphological aspects. The project foresees a total installed power of about 25 MW and an expected generation of more than 140 GWh/year. The power stations will operate under a constant flow secured by automatic relief systems and equipment. The processed water is released immediately after the weir. The stations will be connected to a single management and control system. The nine plants are characterized by net heads ranging from 7 m to 12 m and by flow rates ranging from 25 m^3/s to 33 m^3/s.

MWH is involved in the design review and in the implementation of these plants which are currently under development. The outline programme for the development of the SHPPs capacity is as follows:

- Phase A: This phase consisted of the construction of the first two SHPPs and it is already terminated since these plants have been operating since June 2008 and April 2009 respectively;
- Phase B: The second phase includes the construction of additional three SHPPs, one of them was commissioned in 2012, while the other two are going to be commissioned by mid-2013.
- Phase C: The last four SHPPs are planned to be built in 2013-2015.

The project developer has decided to build the first two plants with the traditional S-type horizontal axis Kaplan turbine (Phase A), the following plants with the more advanced technology of the bulb turbine (Phase B) and the last four plants with the movable bulb turbines (Phase C).

Here below the various solutions adopted are described.

Phase A: A reliable and traditional technology

For Phase A a traditional "S" type double regulated Kaplan turbine with horizontal axis has been installed in both plants. The traditional Kaplan turbine is definitely considered an extremely widespread technology.

This configuration is characterized by some advantages: first of all the entire water passage is pre-formed and simply encased in concrete, then the generator is located externally in the powerhouse and therefore easily accessible for maintenance.

The principal disadvantage with such arrangements is that the slow rotating speed of the turbine, if directly coupled to the generator, tends to require a large diameter generator. If the drive shaft is then arranged horizontally it can become difficult to locate the generator within the space available. This in turn often leads to oblique orientations for the drive shaft, making installations and alignment of the generator difficult. The problem can be overcome by using a gearbox to increase generator rotation speed and hence reduce diameter, as it has been done in this case. However, gearbox losses will be in the order of 1% to 2% and gearbox reliability then also becomes an important consideration.

In this configuration inflatable gates, Obermeyer type, have been used for the spillway. This technology is still covered by a patent and consists of metallic bottom hinged spillway gates which are regulated by means of an inflatable rubber balloon. Their advantage is to require simple foundations and low costs of installation and to guarantee an easy transition of floods, debris, ice, etc.

Phase B: A hint of innovation

Once Phase A has been concluded, the project developer has realized that the traditional configuration could be improved achieving a higher energy production at lower costs. Hence, the bulb turbine technology has been chosen for the next three plants.

This technology has become increasingly popular in recent years. Its generator is incorporated in a "bulb", set within the water passage and supported via external struts set in the water passage. On larger machines these supporting struts can be hollow allowing man-access at all times. This kind of generators has the advantages to be smaller and directly coupled with the turbine, thus avoiding transmission losses.

In this case the magnetic field is provided by permanent magnet rotor poles, rather than being created by an electrical current passing through a coil of wire winding up each pole (as it happened in the traditional brushless generator adopted in Phase A). The application of permanent magnets is restricted to a relatively small size, mainly because its cost quickly increases with the generator rating. Since this technology does not foresee any kind of device adjusting generator’s voltage and power factor, it requires to be connected with strong and stable electric grids which have the ability to reduce oscillations in the voltage value.

Since, on the basis of the available data, the stability of the River Iskar Valley medium voltage network was not completely guaranteed, MWH suggested adopting the necessary mitigation measures in order to implement this kind of configuration in a safe and reliable way. The mitigation measures proposed by MWH have been: to introduce a step-up transformer with on-load tape charger or a STATCOM device. These solutions aim at compensating the uncontrolled input/output flux of reactive power due to a permanent magnet generator. The project developer has decided to adopt the first one. The results obtained in the first phase B plant in operation could prove that this solution is sufficient to compensate the grid’s lack of stability.

In this configuration traditional radial gates have been installed. The higher investment cost required by Obermeyer gates led the project developer to switch to a more common solution.

Phase C: A brand new solution

In parallel to the implementation of the first two Phases of the project, the project developer together with MWH investigated the opportunity for improvement of the design configuration, taking into account the latest state-of-the-art technologies. In fact, European manufacturers have, with few significant exceptions, kept a leading edge in researching new solutions for mini hydropower plants.

In particular, one of these solutions seems to fit perfectly with the characteristics of the Iskar River Valley: the movable bulb turbine.

This is the most compact solution among the ones described, as in this case, the hydropower station is completely submerged. The turbine, equipped with a permanent magnet generator, is integrated in a reinforced steel corpus which is fixed on the point of attachment of bearings connections. The curve grid, preventing fishes, debris and other material to enter the turbine, is fixed at one edge of the steel case.

The turbine, together with its steel corpus, can work either in upper or lower position depending on the water flow. The switch from one position to the other is performed by means of inox wires. In case of a flow rate higher than the nominal flow rate, the turbine works in the upper position. This means that floating deposits, bottom deposits and fishes can pass over and under the steel corpus. Since the hydropower plant is totally submerged, during its operation, the so-called “turbine effect” is observed. In fact, the kinetic energy of water creates a sub-pressure zone and a suppression of the down water level after the turbine which is expressed an increase in water speed after its transition through the turbine, an additional increase in the artificial head and, therefore, in the power production.

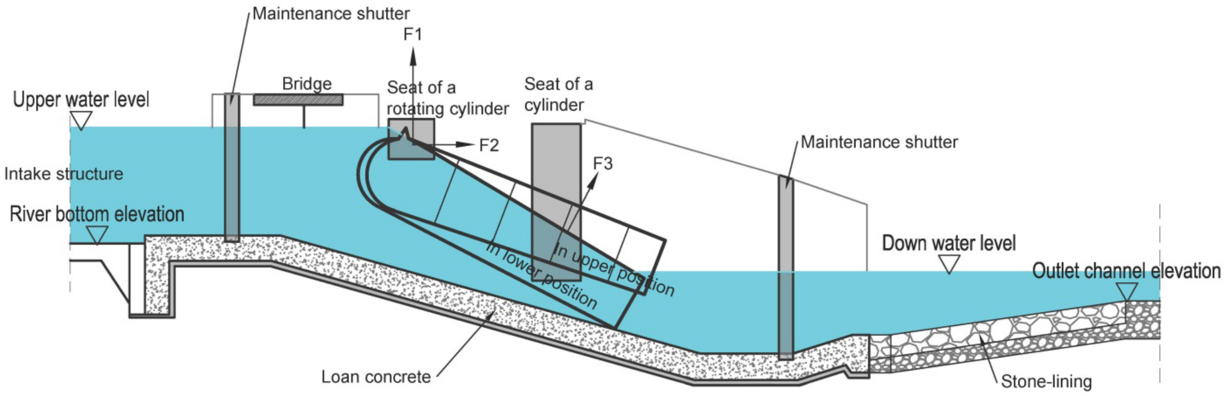

Figure I: Typical configuration of the pivotal bulb turbine

In Phase C the project developer has decided to switch again on Obermeyer gates in order to be consistent with the reduced visual impact of the plant. Their higher cost is compensated by the lower cost of civil structures. In fact, one of the main benefits of hydropower plants with integrated bulb turbines is the great reduction of construction and installation activities. The basic construction of the powerhouse only includes a reinforced concrete corpus, where the production unit is installed, as well as a bottom plate in lean concrete on which the turbine is laid when the flow rate is equal or lower than the nominal one.

Furthermore, many other advantages can be listed:

- a high efficiency: the high efficiency of the bulb turbine is further increased by the additional virtual head created by the pressure of water flowing above and below the steel corpus when the flow rate is above the nominal one;
- long-term exploitation: in the plants of Phase A and B part of the water is discharged by opening the gates if it exceeds the nominal flow, while the powerhouse is completely sealed in case a flood occurs. In Phase C plants the turbine is working in every condition. This means that in case of flood, gates are completely lowered, but water keeps on passing above, though and below the steel case containing the turbine;
- multiple ecological benefits such as free floating of debris, reduced visual impact, reduced impact on fauna, irrelevant noise emission, etc.

Since a permanent magnet generator is still involved, the suitability of this technology to each case has to be taken into account. Therefore, the applicability of this technology is subject to:

- the electric grid current status (the permanent magnet generator needs to be connected to a stable and strong grid, as explained in the previous paragraph);
- the width of the river section: the nominal power of each pivotal bulb turbine is still limited to a few megawatts, therefore, in case a narrow section exists, this could limit the number of turbines to be installed and therefore the installed power of the plant;
- the available head: this technology is currently not applicable for net head higher than 10 m.

The above described technology has already been implemented on a plant in Switzerland.

In Figure II a picture of the plant in operation is shown. Its layout is similar to the one that will be implemented in the Iskar River Valley. The river's section appears to be divided in three parts: the inflatable gates are located in the section farther from the observer, while two sections characterized by blue flaps are hosting the two metallic channels where movable turbines are encased. In case the river's flow rate becomes higher than the nominal flow rate of the turbines, the flaps lower down and the water passes underneath, through and above the metal corpus.

Since almost all the equipment is submerged, noise emissions are not significant.

Figure II: Example of movable bulb turbines in operation

Comparison between the three technologies

The coexistence of these three different configurations in similar sites of the same river can give the evidence of the improvement in the technology used.

The three technologies described can be compared on the basis of the following criteria:

- Flexibility: this criterion is satisfied by the whole project since all configurations can easily fit the characteristics of the site and are proven to be modular.

- Investment cost: this aspect includes the equipment costs, the civil work costs, the commissioning costs, O&M costs as well as the cost of the required man power and specialized personnel. Among the mentioned items, the civil cost is the one which expects the higher variation on the basis of the configuration adopted. The two plants of Phase A have required the construction of a big powerhouse able to host the turbine, the control rooms, the transformers and, in Phase A, also the generator. A slight improvement has been experienced in Phase B where turbine and generator are completely submerged. Phase C has eliminated the cost of the powerhouse leading to a drastic reduction of civil costs.

  In the table below a comparison between investment costs for the different phases is shown.

Table I: Breakdown of investment cost for the three phases

Activitiy	Phase A	Phase B	Phase C
	[Euro]	[Euro]	[Euro]
Preliminary works	180,000	150,000	220,000
Detailed design	370,000	600,000	450,000
Work supervision	150,000	450,000	300,000
Electric connection	190,000	170,000	170,000
Foundations	2,200,000	2,800,000	1,800,000
Civil works	3,600,000	3,500,000	2,000,000
Mechanical activites	1,500,000	1,500,000	>1,500,000
Electromechanical activities	2,000,000	1,800,000	~1,800,000
Instrumentation and control	600,000	550,000	~550,000
Contingencies	600,000	600,000	~600,000
O&M	150,000	150,000	<150,000
Totale	**11,540,000**	**12,270,000**	**n.a.**

Some assumptions have been performed on costs for mechanical and electromechanical activities, instrumentation and control, contingencies and O&M in a Phase C plant. Exact data are not available to the MWH team yet, however it is assumed that:

- the mechanical part will require a slightly higher investment since the supplier has to manufacture not only the turbine but also the whole steel corpus;
- the electromechanical activities, mainly including the cost of spillways, has been assumed to be similar to the one foreseen in Phase B since, despite it applying the more expensive Obermeyer devices, less gates will be necessary. The movable turbines, in fact, act also as gates during flood;
- costs comparable to the ones for Phases A and B are hypothesized also for the supply and installation of instrumentation and control equipment and for contingencies;

- lower O&M costs have been assumed for Phase C.

The other items quoted in the table have been inferred from the contracts signed between the suppliers and the project developer. Though they can be used as a general indication, it should be kept in mind that they are strongly connected to the specific characteristics of the site and project's development process. An example of cost's specificity is the design: in Phase C very simple structures and foundations are foreseen, however their cost still seem to be comparable to the one of previous phases. This is due to the fact that a preliminary design had been implemented two times for plants of Phase C: an initial one with the configuration of Phase B and the new one with the innovative technology.

However, as shown in the table, it could be concluded that the costs of Phase C plants are generally lower than the costs of a plant of Phase A or B.

- O&M: this cost is in accordance to common values are do not experience any relevant variation from Phase A to Phase C.
- Efficiency: This aspect has progressively improved from Phase A to C. The first improvement in the efficiency of the turbine-generator group is due to the use of the bulb set instead of the traditional one, while a further step has been taken with the new technology adopted in Phase C. In this configuration the efficiency declared is the typical bulb turbine efficiency (like in Phase B), nonetheless some tests performed by the manufacturer has demonstrated that, when the movable channel is in its upper position, the water passing below and above the channel creates a further pressure which is actually increasing the nominal head. This leads to a higher energy production than what is expected.
- Reliability: All the applied configurations are considered reliable, however it should be mentioned that, while the "S" type Kaplan turbine has been applied to several plants in many different locations and it is a proven technology since decades, the cutting edge movable turbine is so recent that it is still covered by a patent and it has been experienced on a limited number of plants. Furthermore, a very limited number of suppliers are currently manufacturing the technology applied in Phase C, thus their offer is not easy to estimate.
- Environmental impact and sustainability: Also this aspect is gradually improved in the project frame. The first plants have two kinds of impact on the environment: a visual impact due to the high powerhouse which is visible from the surroundings and an impact on local fauna. The implementation of the configuration characterized by the bulb turbine lead to a decrease in the visual impact which will be further decreased in Phase C. The last four plants will have almost no impact both visually (the plant is completely submerged) and on fauna, since fishes and debris can pass below and under the encased turbine. For all the plants, independently by the technology used, a particular attention has been paid to limit noise or vibration in order to decrease as much as possible the impact on local population.
- Time-schedule: Different configurations may lead to different project schedules. When investigating the use of different suppliers, the time required to supply the equipment should be a key aspects to be considered. The decrease in the civil works of

Phase C and its simplicity of construction and implementation will shorten the time necessary for its construction and start-up.

Conclusion

Thanks to the contemporary presence of the three steps and to the similarity of the nine stations in terms of installed power, water discharge and head, this case study has shown the progressive improvement of technology in exploiting low heads without harming the environment. The project has shown as moving from Phase A to Phase C, the project developer has found more compact, efficient and environmental friendly configurations.

In particular the cutting-edge plants of Phase C, using the very recent movable bulb turbine, reflects an absolutely innovative conception aiming to preserve the natural ecological balance in river beds and to produce green energy, reducing to minimum the respective investment costs and the implementation time. Despite it having many advantages, the installation of a pivotal bulb turbine has to be evaluated on the basis of the context since it is still limited to very low head applications.