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Production flexibility of small run-of-river power plants: KWGO smart-storage case study

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Abstract. In the framework of the new Swiss feed-in-tariff system for Small Hydropower Plants (SHP), the aim of the SmallFLEX project, led by HES-SO Valais and performed in collaboration with EPFL, WSL, EAWAG, PVE and FMV, is to show how SHP can provide winter peak energy and ancillary services, whilst remaining eco-compatible. The pilot and demonstrator site selected is the new SHP of Gletsch-Oberwald (KWGO) owned by FMV and commissioned end of 2017. This run-of-river power plant is equipped with two six-jets Pelton turbine units featuring a maximum power of 7.5 MW each while the average annual power is lower than 5 MW, with a maximum of production during the summer. The capacity of infrastructure, equipment, and other adaptation measures to produce in a flexible way is being assessed while measuring the impact of this new operation on the environment, production and revenues. The paper focuses on the two experimental campaigns and the numerical simulations carried out to assess the flexibility of the power plant by means of smart use of existing infrastructure as additional storage volumes: the settling basin, the forebay and the upper part of the headrace tunnel.

1. Introduction

The 2050 Swiss Energy Strategy is based on a massive development of renewable energy sources. Due to the intermittent nature of these energy sources, mainly composed by wind and solar energies, their integration is a challenging task as far as the power network stability is concerned. In this context, Swiss hydropower plants are expected to play an important role to improve the stability of power network due to their production flexibility, fast response time and extended operating range. Consequently, the demand for ancillary services, such as primary, secondary and tertiary control capabilities considerably increased during the last decade, in Switzerland and in Europe. Small Hydro Plants which already represent 10% of the hydroelectricity production in Switzerland, are also eligible to provide ancillary services and thus may contribute to support the power network stability. End of 2017, a new ordinance on energy production modified the Swiss national feed-in tariff (FIT) system for small hydropower to encourage plant owners to produce according to the energy demand, thus opening up new business cases, see [1]. In this context, a demonstrator project, called SmallFLEX, has been set up to investigate the flexibility of small run-of-river plants.



Providing storage to mountain intakes is not a brand-new idea but it has not been the object of systematic research and knowledge transfer to practice, particularly in the context of a liberalised energy market and with capacity (or regulation) markets. The commissioning of the Stanzertal SHP in Austria with a modified headrace profile allowing for alternated operation in pressurized and free-surface flow, see [2], is a recent example on how engineering practice is searching for technical solutions to adapt infrastructure design to new operation conditions and/or functionalities. The headrace tunnel profile was purposely provided in different slopes and with intermediate air vents to allow its use as an underground storage during winter. The availability of a surge tank at the transition between the headrace tunnel-reservoir and the steel-lined pressurized shaft allows maintaining the turbine regulation system governed by an upstream water level with limited head variations. Advances over the last decade in terms of air entrainment and detrainment in pressurized waterways also pave the way for innovative waterway design, exploring conditions previously considered unacceptable due to the risk of upstream or downstream air blowouts. Another example is the Leikanger HPP in the Western part of Norway, among the very few power plants designed for having available storage volume in the headrace tunnel, see [3], expected to be commissioned within the start of 2021.

In the SmallFLEX project, the following points are investigated:

- How can intra-day, intra-week or intra-monthly storage be added to a given scheme?
- Can a smart use of existing structures allow to provide such storage at minimum adaptation costs?
- Can the headrace be partially dewatered and what are the consequences of enlarging the operational range of the machines?
- What can be the added value of meteorological forecast in terms of power generation and prediction of sediment inflows?
- What are the consequences of a more flexible operation to the downstream river reach, in terms of hydropeaking consequences and river morphology?

The three first questions will be addressed in this paper. After, the presentation of the project detailing the demonstrator site, the general methodology, the identified storage and the expected added value of a more flexible operation of the power plant will be provided.

2. The SmallFLEX project

2.1. Case study: Gletsch Oberwald Hydropower Plant



Figure 1 Picture of the intake, the silting chamber, the forebay tank with the inlet of the headrace tunnel and the machinery cavern of KWGO SHP, source: FMV

The Gletsch-Oberwald hydropower plant (KWGO) is a small run-of-river plant located at the source of the Rhone River in Switzerland and commissioned end of 2017. Two Pelton turbines, equipped with 6 injectors, provide a maximum power of 7.5 MW each for a net head of 287.45 m and a total discharge varying between 0.145 m³/s and 5.8 m³/s.

Due to the hydrology of this site, most of the production is carried out during summer while the discharge is often too low during winter to operate the turbines. Based on the yearly production, the mean capacity of KWGO is lower than 5 MW explaining that the plant is considered as a small one. The power plant is constituted of the main following parts, see Figure 1:

- an intake in Gletsch,
- a silting chamber and a forebay tank
- a headrace channel of 2'117 m with a diameter of 2.8 m and a constant slope of 13.2 %, see [4]
- a machinery cavern with two Pelton turbines in Oberwald
- a tailrace channel.

2.2. General methodology

The aim of the SmallFLEX project is to show how SHP can provide winter peak energy and ancillary services, whilst remaining eco-compatible. The outcome of recent research by swiss research partners have been applied to a pilot facility provided by FMV with the goal of providing operational flexibility to the SHP owner and therefore harvest additional revenues. The additional flexibility will be done by testing infrastructure and equipment or operational adaptation measures, assessing their impact in terms of outflows, electricity output and revenues, see [5],[6].

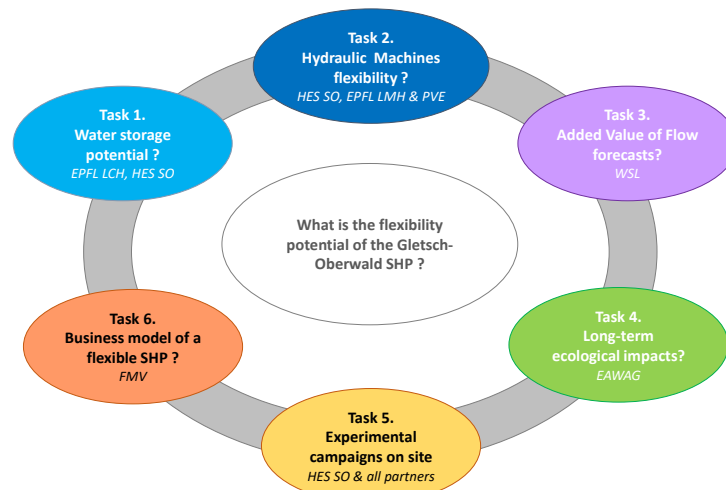


Figure 2 Description of the SmallFLEX methodology to assess the flexibility of the KWGO SHP.

To assess the flexibility of the chosen power plant, six activities have been defined, see Figure 2, among which, four will be addressed in this paper:

- The aim of task 1 is to identify the storage volume of this run-of-river power plant. The available space under-ground, partial dewatering of the headrace tunnel and exploring open air backwater are the options within the present concession limits.
- Task 2 focuses on the services to the grid that could be offered by the identified storage using transient simulations and real-time monitoring of the power plant with Hydro-Clone[®]. In parallel, the behavior of the hydraulic machines under low head conditions, assuming a dewatering of the headrace tunnel, will be investigated to predict the limit of the “falaise” effect using flow numerical simulations.
- Tasks 3 and 4, which are not presented in this paper, are devoted on one hand to the forecasts of inflow which are highly sensitive to snowmelt in this region and on the other hand to quantify environmental structural and functional responses in the recently restored floodplain section subjected to short-term hydropeaks, see [7].
- Task 5 covers the preparation and the realization of two experimental campaigns on site with the objective to validate the simulations and to determine the minimal head to operate the machines in safe conditions.
- The economic advantages to operate this power plant in a more flexible way thanks to the identified storage used considering the limits of safe operations are investigated in task 6.

2.3. Hidden storage options

Apart from expensive provision of new storage volumes, both above and underground, a thoughtful assessment of the existing infrastructure and its operational across the year show that some of the existing already-paid-for underground structure of the powerplant could be also used as storage volumes. This is the case of the underground sediment settling basin, of the forebay as well as in the upper part of the single-sloped headrace tunnel, see Figure 3.

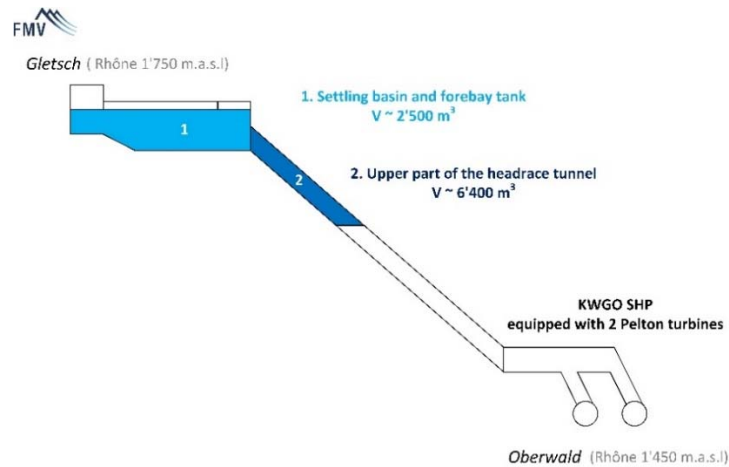


Figure 3 Storage volumes of the small run-of-river KWGO hydropower plant.

The first part of the storage represents a volume of $2'500 \text{ m}^3$. To allow the access and use of the two chambers of the settling basin as a storage volume, two gates have been installed during the early stages of the research project alongside the construction of the power plant, in anticipation of adding flexibility. From end of fall to beginning of spring, when the sediment rate is very low or nil (most of the upstream river catchment is frozen), the gates are opened, allowing to store water even when the inflow is lower than the minimum discharge of one unit or to empty this volume when the discharge is higher than the inflow to enlarge the operating time or to perform a peak of production. During summer, the gates are closed, the priority is to filter sediment particles down to approximately $300 \mu\text{m}$ to preserve the turbines, see [5].

In addition, a second volume located in the upper part of the head race tunnel can be used to provide flexibility in summer and to increase the storage from fall to spring. A volume of $6'400 \text{ m}^3$ corresponds to a head reduction of more than 35%. The risks identified to use this additional storage is to:

- provoke air entrainment and transport all the way down to the turbines during dewatering: this risk has been excluded by model tests.
- damage the tunnel concrete lining during dewatering or filling by compression or tensile stresses due to the interaction between the tunnel and the surrounding rock mass: this risk has been excluded by limiting the velocity of water level decrease/increase to values attained during first filling and dewatering of the tunnel at construction commissioning, re-assessed by an external expertise for the conditions of the flexibility tests.
- damage when the turbine reaching the “falaise” effect, which will lead to vibration and premature ageing of the machine: this risk has been assessed through transient simulations, flow numerical simulations, and field tests.

2.4. Expected flexible operations

Thanks to the use of the identified storage, two main flexible operations are targeted:

- To increase the energy production during winter. The inflow is very low, either the turbines are stopped since the inflow is lower than the minimum discharge tolerable by the machines or the turbines operates at the lowest eligible power which corresponds to a lower efficiency than higher power operating conditions. Using the storage will allow to provide peaks of production with a higher efficiency, which can ideally be scheduled during the highest electricity prices, or to increase the operating duration reducing the number of starts and stops previously imposed by the inflow.

- To provide primary control ancillary services during the whole year. The capacity of the power plant to provide such services have been assessed with SIMSEN transient simulations. The details are provided in part 3.

Both flexible operations of this small run-of-river power plant will provide more revenues to the owner by increasing the energy production, by producing electricity when the market is favorable and by providing ancillary services to the grid.

3. Numerical investigations

3.1. Transient simulations of KWGO

To evaluate the potential of available power to provide ancillary services, simulations of primary control scenarios using a SIMSEN 1D-numerical model of the Gletsch-Oberwald power plant have been carried out. Particular care was taken to correctly model the settling basin and the forebay tank, by taking into account the discharges exchange through the bottom gates and the weir. The SIMSEN model can be configured to be either in "summer" operating mode, where the gates are blocked and all the flow passes through the weir, as well as in "winter" operating mode, where the gates are opened to allow the exploitation of the settling basin as a storage volume. It is worth mentioning that this model is also used by the Hydro-Clone[®] real-time monitoring system, which is operational since June 2018. Consequently, its calibration and accuracy have been duly validated during commissioning tests. Among the ancillary services, the primary control ensures that the balance between production and consumption is restored within seconds following a disturbance. This activation is carried out directly and automatically in the power plant using the turbine controllers. According to Swissgrid's requirements, it must be possible to consistently activate the primary reserve power within 30 seconds and to deliver it for at least 15 minutes for any quasi-stationary frequency deviation of ± 200 mHz. In addition, the power production must be within the tolerance bands shown in Figure 4a. The amount of power delivered by a generating unit as a function of the frequency deviation in the network is typically characterized by the value of the permanent droop, defined as $BS = (\Delta f / f_{ref}) / (\Delta P / P_{ref})$. For instance, a permanent drop of $BS=4\%$ corresponds to the provision of $\pm 10\%$ of the nominal power in case of a frequency deviation of ± 200 mHz.

In the case of the Gletsch-Oberwald power plant, the analysis of the primary control potential consists first in evaluating the energy reserve available to provide ancillary services without exceeding the turbine guarantee limits. In a second step, the dynamic response of the facility is simulated for various permanent droop values by incorporating the turbine governor into the SIMSEN model of the power plant. This SIMSEN implementation of this PID type governor is shown in Figure 4b, with the speed and power control loops being combined via the permanent droop. The parameters of this controller have been optimized to obtain the most dynamic and stable response possible. Numerous frequency response scenarios were simulated to find out how much power reserve the power plant could provide, while meeting the Swissgrid qualification criteria (frequency response), see Figure 4c. Finally, the model was used to define the maximum permanent droop value that would guarantee a stable operation for a set of PID parameters. Indeed, the permanent droop acts as a gain on the regulator power control loop, as illustrated in Figure 4b. Consequently, for an active power setpoint change, a low permanent droop can lead to a more stable behavior than a high permanent droop value, although the corresponding contribution to the primary control is more important. The stability of the system response to active power setpoint changes was therefore checked by simulating several permanent droop values in combination with the selected PID parameters, as shown in Figure 4d.

The results of the estimation of the available power for ancillary services can be summarized as follows:

- Considering the available water volume in the settling basin, the capacity of the primary control is $\Delta P=2x \pm 4$ MW, corresponding to a permanent droop of $BS=0.755\%$.

- Considering the ability to pass the Swissgrid qualification test (frequency response), the capacity of the primary control is $\Delta P = 2x \pm 3$ MW, corresponding to a permanent droop of BS=1%.
- Considering the stability during a change of the active power setpoint, the capacity of the primary control can be selected between $\Delta P = 2x \pm 0.5$ MW and $2x \pm 0.75$ MW, corresponding to a permanent droop between BS=4% and BS=6%.

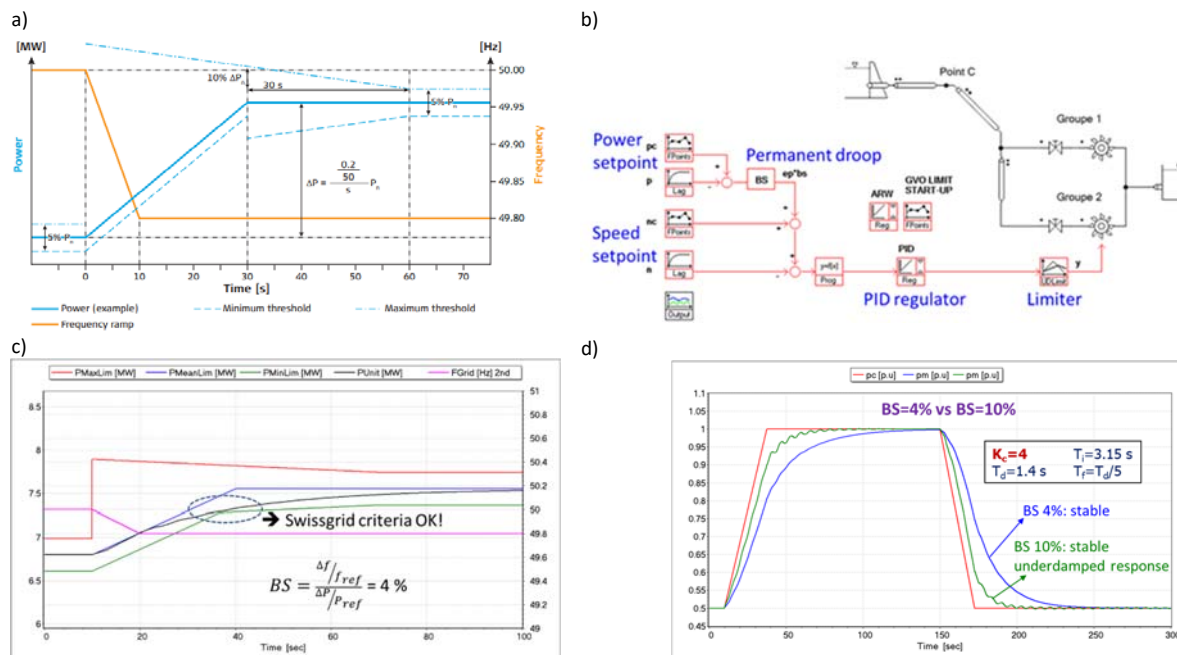


Figure 4 a) Tolerance band of the Swissgrid qualification test, b) SIMSEN modeling of the turbine governor, c) Simulated frequency response scenario meeting Swissgrid criteria with a permanent droop of 4%, d) Stability of the response when the power setpoint is changed with the permanent droop up to 10%.

3.2. Jet flow simulations in the Pelton turbine

The quality of the jet is primordial for the efficiency of the Pelton runner. The quality of the jet is described by its axial symmetry, a straight and sharp interface between the water and the air, a small dispersion and the absence of a swirl motion. By decreasing the head, the flow inside the distributor and at the outlet of the needle could be altered due to a lower available energy.

Six different heads from 66% to 100% of the nominal head have been computed using the OpenFOAM toolbox. For each head, three needle strokes have been considered: 90%, 49% and 20% of the maximum opening. The contours of the water volume fraction in a plane parallel to the jet axis for a stroke of 90% and 20% are compared in Figure 5 between the jet at nominal head and at 75% of the nominal head. No influence of the head on the liquid volume fraction is observed since the pattern is the same. On the contrary, the needle stroke has an influence on the air content inside the jet with a lower liquid volume fraction value for a small stroke.

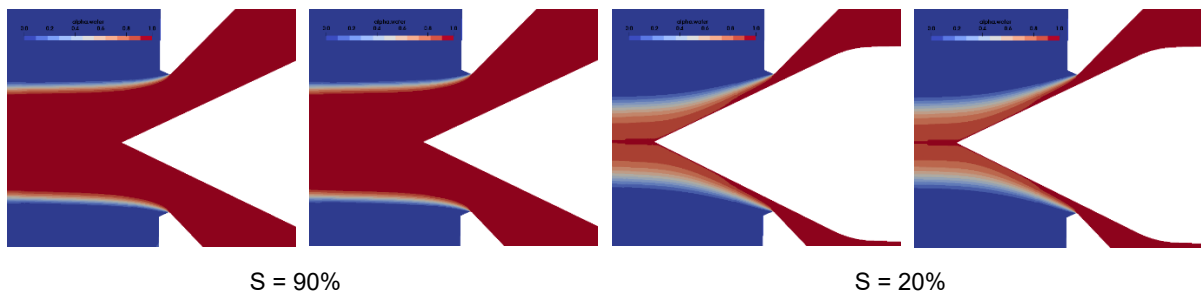


Figure 5 Contours of the water volume fraction for the nominal head (left) and 75% of the nominal head (right) in a plane parallel to the jet axis. OpenFOAM simulations.

The corresponding dimensionless axial velocity profiles are displayed on Figure 6. The velocity profiles are extracted along a line perpendicular to the jet axis and located 1.42 nozzle diameter downstream the nozzle outlet. Whatever the head, the velocity profiles superimposed one to each other. Therefore, lowering the head does not worsen the jet quality.

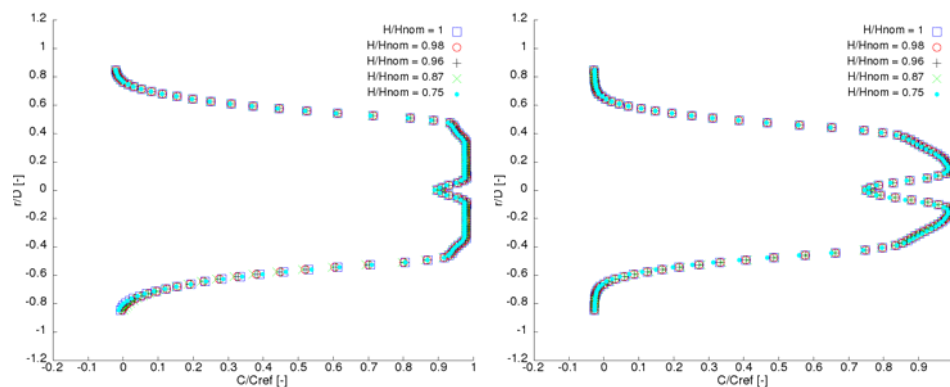


Figure 6 Dimensionless axial velocity profile for 5 different heads and a needle stroke of 90% (left) and 20% (right). The profile is extracted from a line located 1.42 nozzle diameter downstream the nozzle. OpenFOAM simulations.

3.3. Flow simulation of the Pelton runner

The velocity of the jet decreases by lowering the available head. If the velocity of the jet is too slow, the “falaise” effect appears that is characterized by a decrease in efficiency and an increase in the level of vibrations. To investigate for which head value the “falaise” effect occurs, simulations of the interaction between the jet and the runner are carried out with the finite volume particle solver GPU-SPHEROS, see [8]. The computational domain is composed of two jets and three runner buckets to investigate the influence of the first jet on the second one, see Figure 7. The inlet boundary conditions are transferred from the OpenFOAM simulations.

The variation of the efficiency against the head is plotted on Figure 7 for the three needle strokes considered in this study. For a stroke of 49% and a head higher than 88% of the nominal head, the efficiency is rather constant. For a lower head, the efficiency drops abruptly to less than 50% in accordance with the “falaise” effect. For the strokes of 20% and 90%, the efficiency decreases almost linearly with the head. For a head corresponding to less than 75% of the nominal head, the efficiency is lower than 60% whatever the needle stroke.

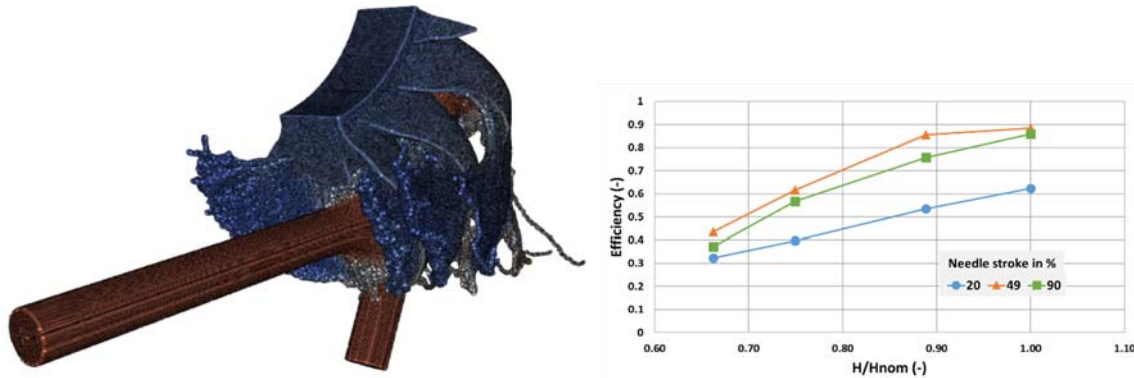


Figure 7 Water particles deviated by rotating Pelton buckets and variation of the efficiency against the head for the three needles stroke considered. GPU-SPHEROS simulations, see [10].

3.4. On-site experimental methodology

Two experimental field tests have been carried out during the project to:

- Assess the identified storage volume
- Assess the accuracy of the inflow forecasts
- Validate the numerical simulations
- Investigate the behavior of the power plant during flexible operations
- Investigate the hydropeaking effects in the alluvial area
- Demonstrate the flexibility of the power plant and its limits.

A global concept for the instrumentation has been set up with, see Figure 8:

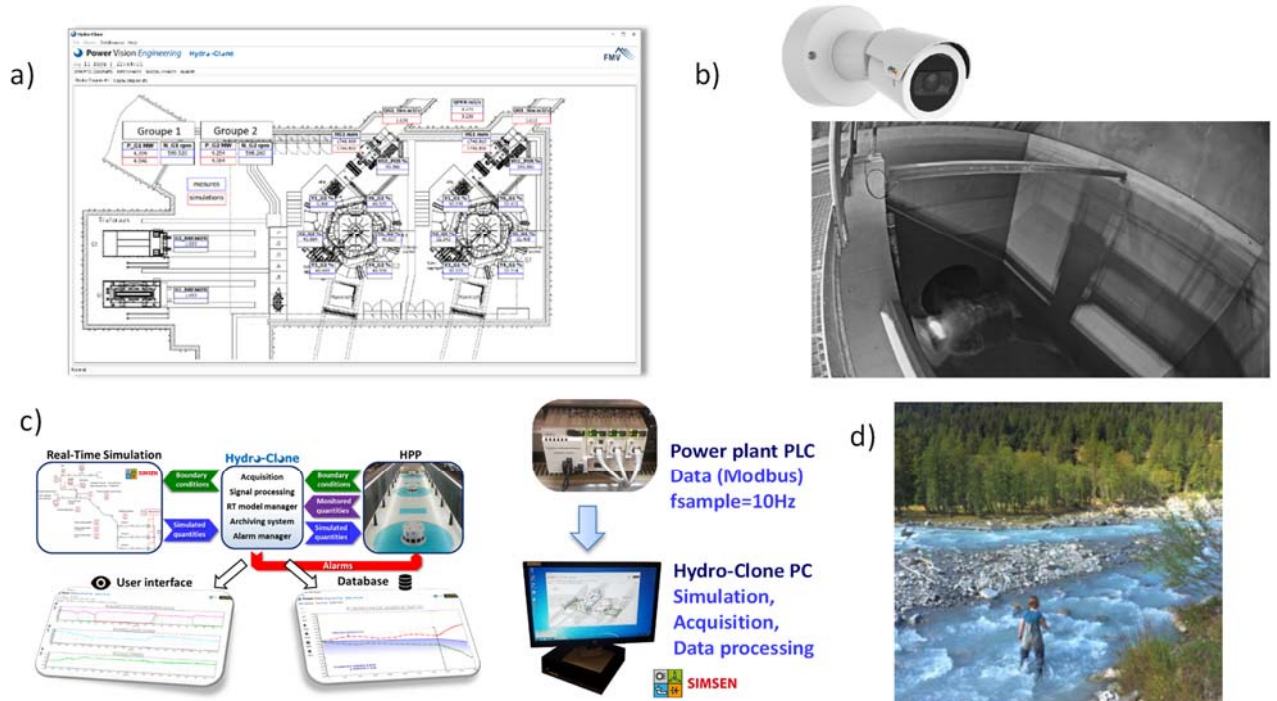


Figure 8: Instrumentations of the on-site experimental campaigns: a) The monitoring of main quantities of the turbine, b) a camera in the forebay chamber, c) the Hydro-Clone® system for the whole power plant, d) field measurements and water level monitoring in the downstream alluvial area.

3.5. First experimental campaign

The first campaign was performed end of 2018 for three weeks to use the first part of the smart storage: the settling basin and the forebay chamber, see Figure 9. During the first two weeks, five production peaks of 15min using one unit at almost maximum of power have been provided to generate hydropeaking events in the alluvial area with different recovery intervals from one week to one day. Thanks to these tests, EAWAG has been able to assess the limited effect of such hydropeaking event on the alluvial area, see [7]. During the last week, several production peaks of different amplitude and duration have been carried out to assess the storage volume estimation and the model to predict the incoming discharge. The formation of vortices at the intake was also monitored as well as the behavior of the machines without any problem detected.

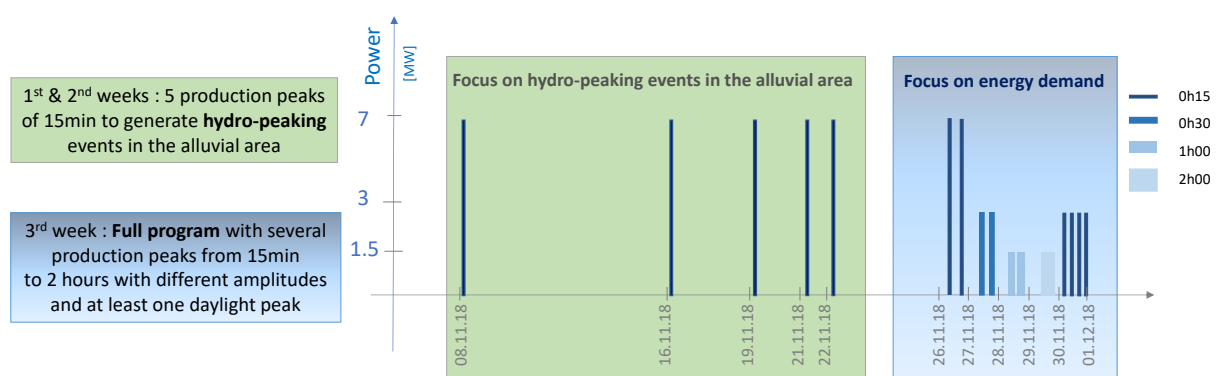


Figure 9 Program of the first on-site experimental campaign.

3.6. Second experimental campaign

During the second campaign in May 2020, for the first time the flexibility of this run-off-river power plant has been challenged up to the final target defined in the project. The instrumentation used during the first campaign of 2018, dedicated to the monitoring of the free surface at the powerplant intake, of the main quantities of the tested machine as well as of the water level in the downstream alluvial area, has been redeployed in parallel with the Hydro-Clone® system, see [9]. The prediction of the intake flowrate as well as the usage of the identified storage, including the settling basin, the forebay tank and, the most challenging, of one third of the headrace tunnel, have been set up and coordinated between the partners. A special production program including different power peaks for two testing days has been prepared based on transient simulations of the power plant. Three peaks over two days have been scheduled allowing to investigate the influence of the speed at which the headrace tunnel is emptying and filling and the number of needles opened during the peak. The two Pelton units have been run in parallel, unit 2 was monitored while unit 1 was used to adjust the operating conditions as desired. The minimum head reached was 190m, representing a reduction of more than 35% compared to the nominal head. The global efficiency of the power plant with this new storage capacity has been recovered including the region of the “falaise effect”. Figure 10 shows the head variation and the power of the two units during the two days of tests as well as the measured global efficiency. This second campaign provided to the powerplant’s owner the head and the storage limits for a flexible operation.

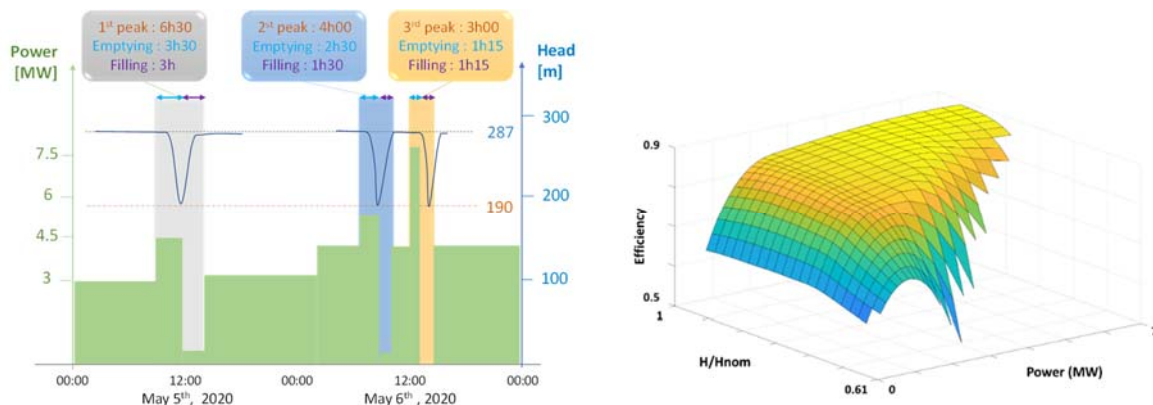


Figure 10. Right, program of the second on-site experimental campaign; left, efficiency as a function of the head and the power monitored during the second campaign.

4. Discussions

Once the “new” flexibility of the power plant has been assessed, the optimization of the revenue as a function of the electricity market price has been carried out for the years 2018 and 2019 for which the incoming flow and the SPOT price are known. Over the two years, the use of the storage volumes allows increasing the production by 0.6% with a benefit of 1%. The increase is not very high, but an analysis of the results per season gives interesting insights:

- From December to March, the production of the power plant can be increased by 130% since the storage volumes allow operating the power plant even if the incoming flow rate is lower than the minimal value.
- In April and May and in October and November, the power is between 2 MW and 10 MW, which allows some peak of production. However, the benefits are not significant. The production can even be lower due to the low efficiency of the turbines at heads below 287 mCE.
- From June to September, the power is above 10 MW i.e above the maximum power set for the peak of production (2x5 MW).

The optimization of the revenue depending on power used for primary frequency control ancillary services have been investigated as well. The percentage of the power and the revenue over the period from the 15th of May to the 15th of October shows that approximately 60% of the service occurs during the operation of the power plant in the summer mode. The amount of revenue during the winter period (December to March) represents approximately 1% of the total revenue. It is therefore noticeable that the period suitable for PFC ancillary service is not in conflict with the period for optimizing the production depending on the electricity market prices. Consequently, the two sources of additional revenues can be coupled.

5. Conclusion

Finally, in the framework of the SmallFLEX project, a complete study to investigate the flexibility of the small run-of-river power plant of Gletsch-Oberwald at the source of the Rhone River has been performed. As an alternative to costly additional storage volumes, the project proposes the smart use of existing structures to provide two storage volumes have been identified: (i) the underground sediment settling chamber and the forebay, (ii) the upper part of the headrace tunnel, representing 8'900 m³. Combining numerical simulations and on-site experimental campaigns, a safe use of this storage volume has been explored. Transient simulations provided the primary control ancillary services capacity, while flow numerical simulations predicted the effect of the head decrease on the jet quality and on the efficiency of the machine considering the “falaise” effect. The two experimental campaigns allowed us to validate the methodology and confirm the limits of the flexibility of the power plant. Through an economic analysis, the added value of this identified storage has been assessed. The methodology developed is now available to be applied to other small run-of-river power plants.

Acknowledgements

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