ECONOMIC OPTIMIZATION OF MAINTENANCE MEASURES BASED ON CONTINUOUS EFFICIENCY MONITORING

A. Abgottspon, T. Staubli, E. Bieri, D. Felix

Abstract: In an economic analysis for the HPP Filisur and Fieschertal, the optimal timing of runner overhauls was assessed by balancing the revenue shortfall due to the actual efficiency depletion against the refurbishment costs. Since sediment load and thus turbine erosion varies from year to year, the optimum period between overhauls is not constant. To find the optimum time for a major overhaul of a specific runner, the efficiency history of the corresponding turbine is an indispensable basis. The higher the electricity price, the more important the knowledge of a reliable efficiency history becomes.

1 Introduction

Wear of turbine parts due to abrasive particles is a major challenge in the operation and planning of maintenance measures of medium- to high-head hydro power plants (HPPs). Depending on the sediment load, run-of-river schemes and storage HPPs with intermediate intakes along the power waterways in the Alps [1, 2, 3], the Andes [4, 5, 6] and the Himalaya [7, 8, 9] are particularly exposed to hydro-abrasive erosion. This affects the economic and energetic efficiency of such HPPs.

Turbine efficiency monitoring helps HPP operators to better understand the effect of hydro-abrasive erosion on turbine parts. Furthermore, the monitoring data can be used to evaluate the economic consequences of rehabilitation works or other decisions taken by the HPP operator.

Such continuous turbine efficiency monitoring systems are for example installed at the HPPs Filisur and Fieschertal in Switzerland, at which hydro-abrasive erosion is a concern. At HPP Filisur, this monitoring was commissioned in 2016 [10] and works to full satisfaction. The HPP Filisur is operated by the Albula-Landwasser AG. Two vertical-axis Francis turbines with a gross head of 415 m and a rated output of 33 MW per machine group (MG) are installed. In addition, the results of a multi-year research study at HPP Fieschertal from 2012 to 2021 are discussed [11]. The HPP Fieschertal is operated by Gommerkraftwerke AG. Two horizontal-axis Pelton turbines with a gross head of 520 m, two nozzles per turbine and a rated output of 32 MW per MG are installed.

2 Measurement systems and data evaluation

For a reliable and long-term stable monitoring of efficiency, the quality of the flow rate determination is crucial. Due to the unsteady operation of the HPPs and the delayed response behaviour of the flow measurement, the detection of steady state sequences is a necessity to reduce the scatter of data. The following main routines are applied to establish the efficiency history:

- Checking of the signal quality with an input data validation.
- Identification of stationary operation sequences with a steady state detector.
- Calibration of signals such as the flow rate against reference measurements, e.g. from classical efficiency measuring campaigns such as thermodynamic efficiency measurements, and corrections if required (example will be given in Fig. 3).
- Calculation of the current turbine efficiency in stationary sequences that have passed the input data validation check.
- Finding the corresponding reference efficiency in the hill chart for comparison.
- Determination of the current absolute efficiency difference $\Delta\eta$ (examples will be given in Figs. 1 and 2).

3 Continuous determination of turbine efficiency

3.1 Efficiency history at HPP Fieschertal

At HPP Fieschertal the temporal changes in turbine efficiency (= efficiency history) due to the hydro-abrasive erosion and refurbishment or replacement of turbine parts were quantified by sliding needle index efficiency measurements and by continuous efficiency monitoring.

From spring 2012 to spring 2021, about 45 sliding needle index efficiency measurements were performed per MG mainly before and after the wet seasons (summer). In such a measurement, the turbine discharge and hence the power is varied from about 40 % load to full load and back to 40 % load within about one hour to record operation data under quasi-stationary conditions. From each sliding needle measurement, a weighted index efficiency was evaluated. The changes in these values over time yielded the efficiency histories of each MG.

In addition to these periodic measurements, turbine efficiency differences were evaluated from data of the control system of the HPP in quasi-steady state operation. The objective of applying two methods was to demonstrate that the continuous monitoring yields comparable efficiency histories as classical index efficiency measurements with the sliding needle method. The continuous efficiency monitoring has the great advantage of higher temporal resolution of the history in comparison to some single index efficiency measurements per year. This is particularly interesting during the wet season with full load operation, when the sliding needle measurements cannot be performed to avoid production losses. In this period generally the main efficiency reductions occur (e.g. in summers 2016 and 2017 in Fig. 1). A high temporal resolution in the order of weeks or days is valuable to initiate inspections and maintenance works in case of an unacceptable performance or anomaly. Furthermore, for the sliding needle measurements the HPP operator needs to be involved whereas the continuous monitoring is running without any actions by the HPP operator’s staff. As a drawback, the continuous monitoring generally shows a greater scatter of data compared to classical index efficiency measurements.

Figure 1 shows the efficiency history of MG 1 over the investigated nine years. The displayed values are differences in absolute efficiencies and refer to the first index efficiency measurement with the sliding needle method of that MG. Negative differences indicate an efficiency deficit.

In the year 2012 (with HPP operation during a major flood), as well as in the years 2016 and 2017 (fifth and sixth year of operation since the last major runner overhaul), the efficiency dropped by 1.1 to 1.3 % over the sediment season. In the other years, the efficiency was reduced less or remained practically constant. For runner 2, even an increase in efficiency was measured between 2018 and 2020. Possible reasons for this are:

- In a first phase, hydro-abrasive erosion in the buckets may slightly reduce their roughness (polishing of the coating).
- Grinding splitters and cut-outs during the winter may result in a slight improvement of the hydraulic profile over a few years before the efficiency drops significantly due to cumulative deviations from the designed profile.

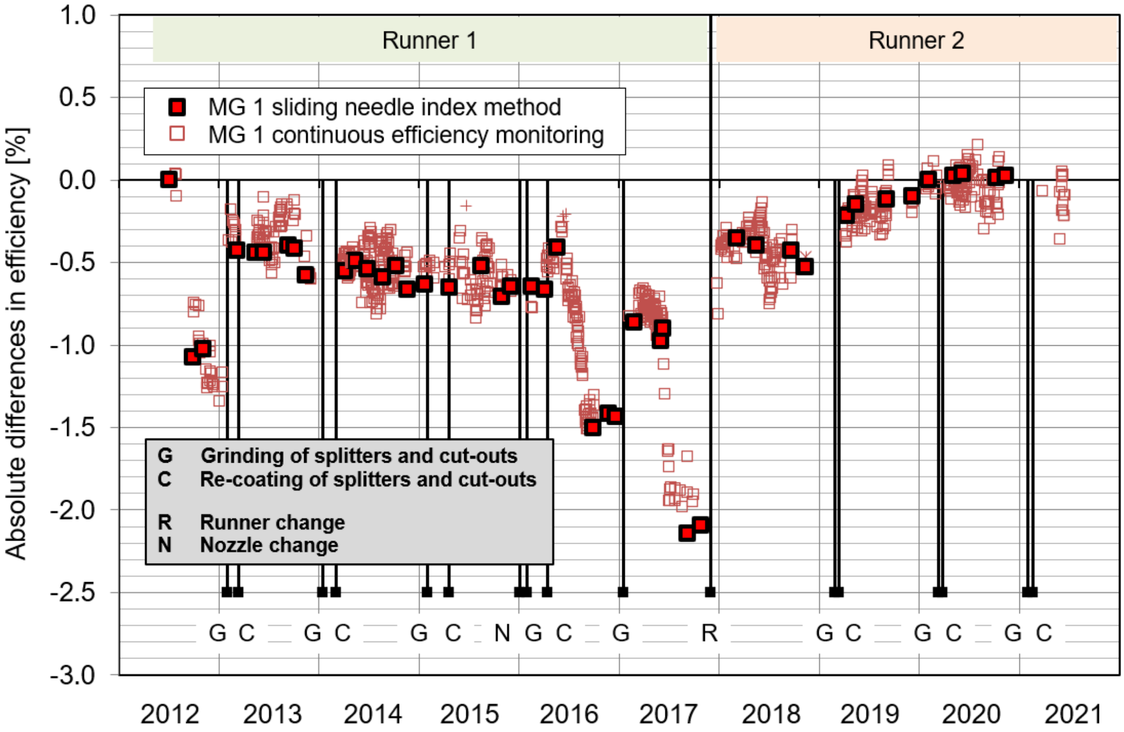

Fig. 1. Time series of efficiency differences *Δη* obtained from sliding needle and continuous efficiency monitoring from spring 2012 to spring 2021 of MG 1 at HPP Fieschertal. Maintenance works are indicated to relate the efficiency differences with the specific maintenance work. Extended from [11].

3.2 Efficiency history at HPP Filisur

From the previous study at the HPP Fieschertal it became clear that the continuous efficiency monitoring alone is working for a industry-related roll-out on turbine efficiency monitoring. To commercialize this monitoring, a collaboration between etaeval and Axpo has been established. The HPP Filisur became the first demonstrator of this collaboration. Meanwhile, further HPPs are equipped with such a monitoring system (HPPs Tiefencastel and partially Mapragg in Switzerland).

Figure 2 shows the efficiency history of MG 1 at HPP Filisur up to the year 2021. The displayed values are again differences in absolute efficiencies and refer to a thermodynamic efficiency measurement in April 2016 (guarantee measurement of a new runner).

In summer 2016 a screw nut got entrapped in the vaneless space in between the guide vanes and the runner blades. The resulting damages led to an efficiency drop of about 1.7 %. After this incidence, the turbine was shortly dismantled and on-site repair works (mostly grinding) on the guide vanes and runner blades were carried out. With these actions an efficiency increase of about 1.3 % was achieved, but an efficiency deficit of about -0.4 % remained. In winter 2016 / 2017 some lack of data occurred due to interrupted communication protocols. In the two years after the incident and the corresponding on-site repair in 2016, the efficiency decreased by about 0.5 % per year (solid trend line in Fig. 2). In winter 2018 / 2019 the runner and the guide vanes were replaced by factory-new components. The efficiency increased significantly to only -0.2 % below the guarantee measurement from April 2016. No significant drop in efficiency was identified in the years 2019 to 2021, in which the runner and the guide vanes were in new or close-to-new condition. In the two years after the incident and the on-site repair, the annual efficiency reduction was clearly higher.

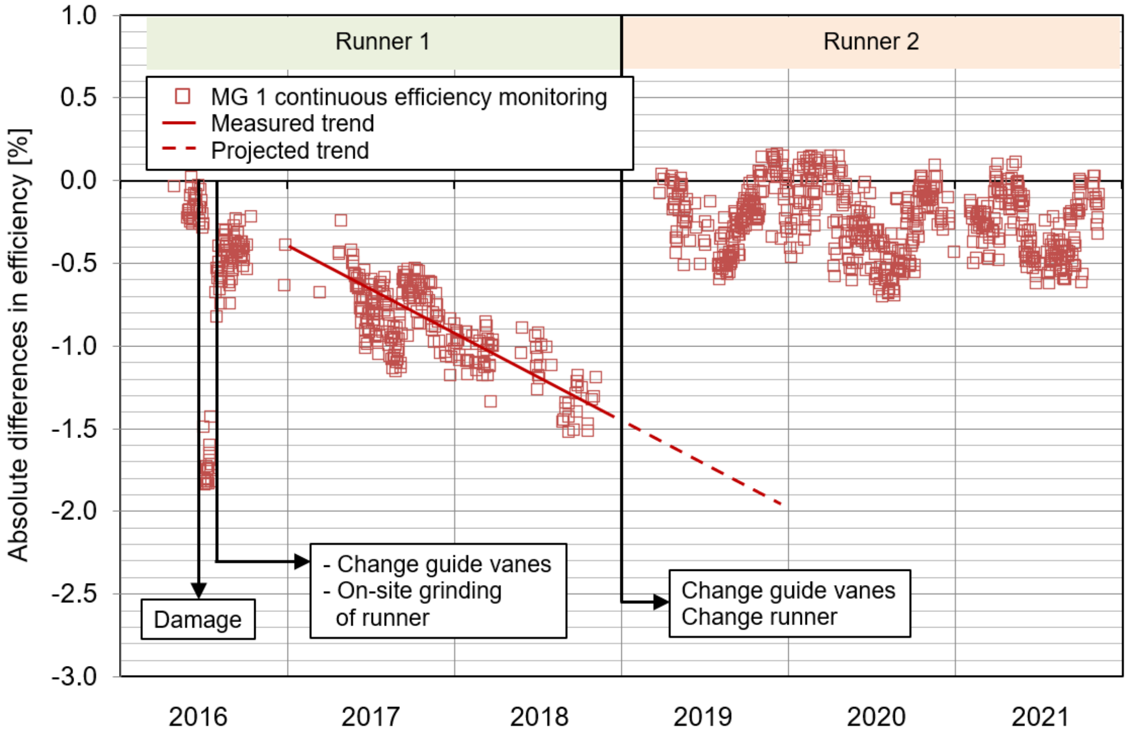

Fig. 2. Time series of efficiency differences $\Delta\eta$ obtained from continuous efficiency monitoring from 2016 to 2021 of MG 1 at HPP Filisur. An exceptional damage and maintenance works are indicated. Extended from [10].

A comprehensive input data validation was and will be established for every HPP. Figure 3 shows a result of such a signal quality check for the flow rate measurement upstream of the MG 1 at HPP Filisur. This flow meter is a clamp-on acoustic transit time device. The graph shows the difference in measured flow rate from an acoustic flow meter in the penstock at a different position with feed through mounted sensors as a function of the water temperature. At 5 °C, both flow measurements were calibrated with the flow determined from the thermodynamic efficiency measurement.

Figure 3 shows that the flow rate from the clamp-on device clearly deviates from the reference flow rate of the feed through device depending on the water temperature. The physics behind this effect can be explained by the transverse path of the emitted acoustic pulses first through the pipe wall, refraction at the pipe wall, propagation through the water, refraction at the opposite wall and finally the propagation to the receiver outside the wall. The propagation velocities of acoustic pulses in solids and liquids are all temperature dependent, as are the angles of refraction. Especially in case of temperature differences between the wall and the water, this comes into play. As a result, the course of the acoustic path changes with temperature. For a feed through or an internal mounted sensors with acoustic pulses travelling only through water no such dependency of flow rate indication and temperature occurs.

Without knowing the relationship between the clamp-on flow meter reading and temperature, the HPP operator would, for example, measure an incorrect flow rate of the order of +2% during summer when the water temperature is 13°C.

The fact that such a deviation would lead to an impracticable use of continuous efficiency monitoring is obvious. The example highlights the need for an input data validation.

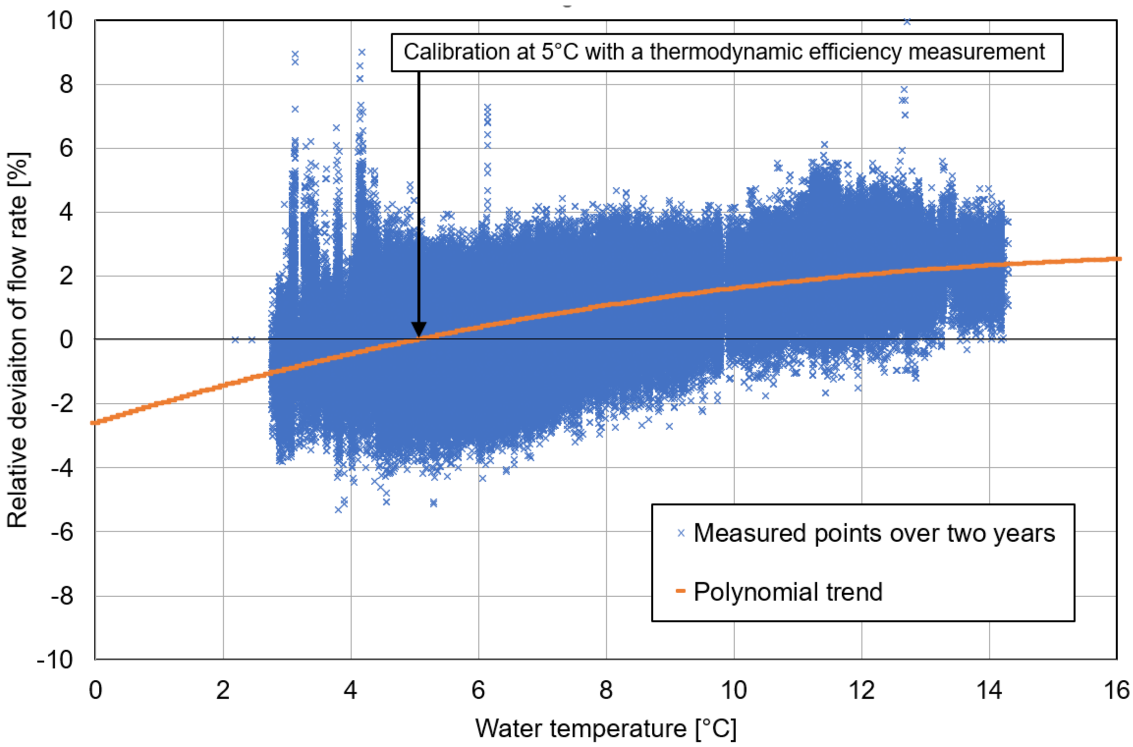

Fig. 3. Deviation of the clamp-on acoustic transit time flow meter against a feed through acoustic transit time flow meter in HPP Filisur as a function of the water temperature.

4 Optimal timing of major runner overhauls

4.1 Economic analysis at HPP Fieschertal

At the Pelton turbines of HPP Fieschertal, minor and major runner overhauls are carried out. The minor overhauls (grinding and re-coating mainly on the splitters and cut-outs) are usually done every winter in the turbine housing. Minor overhauls costed usually about 5 % of the price of a new coated runner.

The major overhauls, i.e. general factory overhauls of the runner with complete re-coating and replacement of wetted nozzle components are necessary every six years on average. After a major overhaul, the initial efficiency level is usually reached again. The major overhauls require a runner change because they are done in the factory. A runner change is done in winter when the operation of one of the two MGs is sufficient to avoid production losses. The cost of a major runner overhaul was in the order of

40 % of the price of a new coated runner. Since such major overhauls are a significant cost factor, the most economical time for a runner change was investigated.

The longer the interval between the major overhauls, the smaller the annual costs caused by them (annuity). On the other hand, the efficiency decreases progressively, and the production losses and revenue shortfalls increase accordingly. Therefore, towards each winter, the question for the HPP operator arises whether,

- the runner should be replaced in this winter (option A), or
- only a minor overhaul should be carried out and the runner shall be replaced in the next winter (option B).

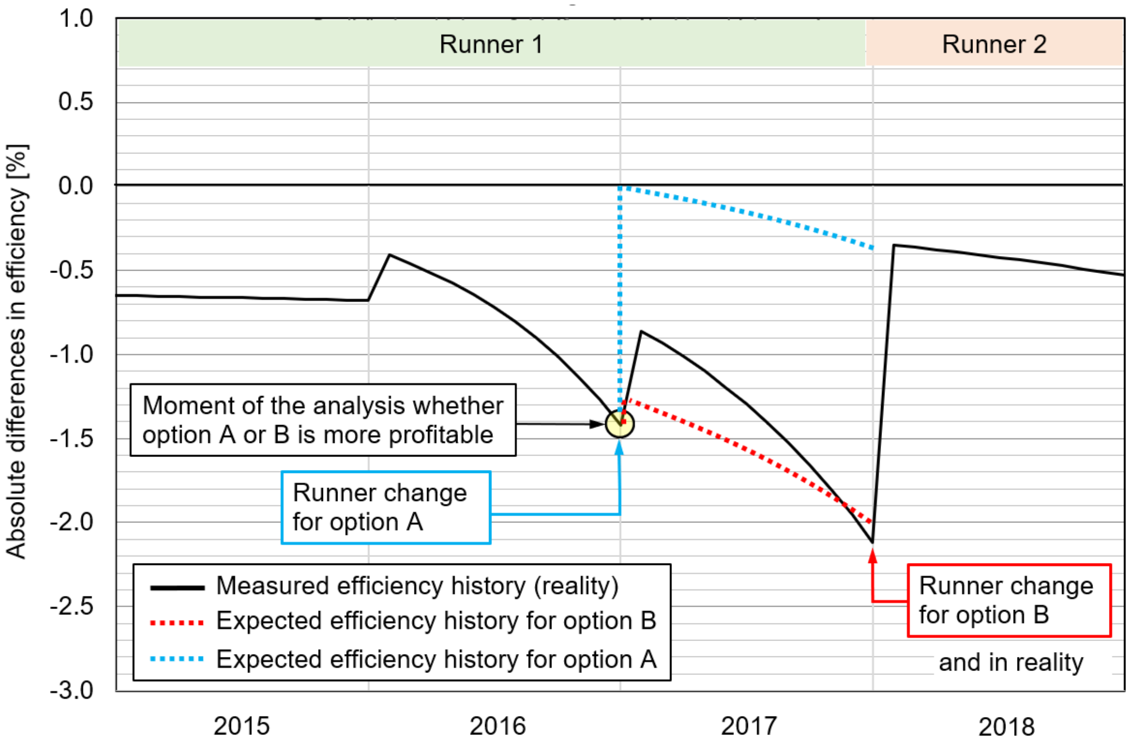

Fig. 4. Efficiency history of MG 1 at HPP Fieschertal with expected efficiency curves depending on the time of runner change.

This question of the optimum time for a runner change is examined from an economic point of view using the example of MG 1 towards the end of 2016. At that time, the runner 1 had been in operation for five sediment seasons since its last major overhaul and its efficiency had decreased by -1.4 %, as shown by the yellow dot on the black line in Figure 4. The black line is the interpolated curve of the efficiency history from Figure 1. Further, the efficiencies expected at that time for the options A and B are shown as dashed lines. If the runner change had been carried out in that winter (option A), there would have been no efficiency deficit at the beginning of the next year (blue line). With the later runner change in the next winter (option B, as executed), a further decrease in efficiency was to be expected (red line). The expected efficiency curves were predicted from the efficiency level at the time of the analysis (-1.4 %) and based on the experience of several analysed previous years.

Table 1 compares the costs of the two options until spring 2018. In option B, the costs of the major overhaul are distributed over more years and are therefore lower. Since the nozzle components are most easily replaced at the same time as the runner, their costs were also distributed over the corresponding years. A minor overhaul is necessary in both options, either in the considered winter or the next winter. Since the runner of the other MG was replaced in the considered winter, the runner of the analysed MG 1 was not re-coated because the effort for re-coating was judged to be too high for only one MG. Therefore, the costs for the small overhaul were lower in option B.

The main difference lies in the efficiency-related revenue shortfall: For the year after the investigated decision point, an average efficiency deficit of about -1.6 % was to be expected in option B (time-averaged value of the red dashed line in Fig. 4), in contrast to -0.2 % (blue dashed line) for option A. With a production of 80 GWh/year per MG, the earlier runner change would have led to approximately 60 kCHF higher revenues. In total, this option would have been about 30 kCHF more economical.

Finally, the expected and actual efficiency development in 2017 was compared (red and black lines in Fig. 4). By grinding the splitter and the cut-outs in the winter 2016 / 2017, the efficiency increased more than expected based on the mean experience value. But during the sediment season of 2017, the efficiency decreased pronouncedly to about the expected level. Thus, the prediction of efficiency at the end of the next sediment season was realistic and would have allowed the selection of the more economical option.

	Option A Runner change in considered winter	Option B Runner change in next winter
Time since last major overhaul	5 years	6 years
Annuity for major runner overhaul and change of nozzle parts	79 kCHF	68 kCHF
Maintenance work on-site	46 kCHF	26 kCHF
Efficiency-related revenue shortfall (calculated with 50 CHF/MWh)	7 kCHF	68 kCHF
Total costs and shortfall	132 kCHF	162 kCHF

Table 1: Economic analysis regarding the timing of the major overhaul of a Pelton turbine in HPP Fieschertal for the two options (referring to Fig. 4).

4.2 Economic analysis at HPP Filisur

At the Francis turbines of HPP Filisur, normally only major overhauls are carried out on the turbine parts. As for HPP Fieschertal, such works are possible during the winter on one of the MGs without production losses.

Similar to HPP Fieschertal in the previous section, the optimum time for a runner change is examined using the example of MG 1 towards the end of the year 2018 (Fig. 2). At that time, runner 1 had been in operation for three sediment seasons since its factory-new status (but with a damage as explained in section 3.2). With the costs of a factory overhaul and the HPP operator’s labour for the change of the turbine parts, the annuities in Table 2 resulted for both options.

The mean efficiency decrease for the year 2018 was -1.2 %. For the economic evaluation without a runner change in the considered winter, it was assumed that the mean efficiency would further decrease by 0.5 % per year (dashed trend line in Fig. 2). So, for the next year a mean efficiency deficit of -1.7 % was expected in option B. In option A and in reality, the mean efficiency deficit after the runner and guide vane changes in 2019 was -0.2 %. With a mean net production of 147.5 GWh/year per MG, the efficiency-related revenue shortfalls listed in Table 2 resulted.

In option B, the costs of the major overhaul are spread over more years and are therefore less high. The main difference among the options lies again in the efficiency-related revenue shortfall. Overall, option A was about 43 kCHF more economical. Thus, the operator took the right decision to not wait another year for the major overhaul.

	Option A Runner change in considered winter	Option B Runner change in next winter
Time since last major overhaul	3 years	4 years
Annuity for major runner overhaul at manufacturer (including labour of HPP operator)	264 kCHF	201 kCHF
Efficiency-related revenue shortfall (calculated with 50 CHF/MWh)	21 kCHF	127 kCHF
Total costs and shortfall	285 kCHF	328 kCHF

Table 2: Economic analysis regarding the timing of the major overhaul of a Francis turbine in HPP Filisur for the two options (referring to Fig. 2).

5 Conclusion

The procedure for continuous efficiency monitoring and efficiency histories of a Pelton and a Francis turbine were presented over six to nine years. To establish reliable efficiency histories, data quality checks for several physical quantities are required, independently of the HPP type. It is not sufficient to analyse only the standard deviations of individual measurement signals. Cross correlations of several physical quantities, especially for the check of the flow rate measurement, are essential.

The optimal timing of major overhauls was assessed from an economical point of view for both case studies. Besides the refurbishment cost, the annual production and the electricity price, the actual and expected efficiency deficits are important input parameters. Hence, the efficiency histories are an indispensable basis for the planning and economic justification of maintenance, refurbishment or replacement of turbine parts. On the one hand, they indicate the current efficiency deficit, which is required for the calculation of the expected efficiency-related revenue shortfall. On the other hand, typical efficiency differences and their ranges can be determined from the efficiency histories. The typical values refer to annual efficiency reductions due to hydro-abrasive erosion or to specific refurbishment works. Such typical values, specifically for a given HPP, are useful for forecasting the economic effects of refurbishment actions and for predictive maintenance. As the monitoring and the corresponding interpretation is continued, the uncertainty in the typical values derived from the efficiency histories will reduce over the years. With higher electricity prices, it becomes even more important for the management of HPPs to reliably know the actual turbine efficiency at any time. The presented methodology developed in the context of solid particle erosion can of course also be applied to other degradation processes of hydraulic machines, such as cavitation erosion.

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