Renovation of hydraulic power plant: how to select the best technical options?

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Introduction

With the Energy Strategy 2050, Switzerland wishes to focus on balanced utilization of hydropower potentials and new renewable energy sources to accommodate nuclear energy phasing out. Integration of large amounts of new renewable energies such as wind and solar power represents a challenging task as far as the power network stability is concerned. Indeed, the intermittent pattern of new renewable energies needs substitution and storage capabilities that hydropower can offer due to the variety of possible technical solutions featuring large flexibility and high performances control capabilities. The production capacity potential must be addressed together with the ancillary services capacity to ensure the stability of the electrical grid.

The decision-making process for the modernization of hydraulic power plant involves to overcome huge number of possible combinations of renovation options at early design stages, when each decision has a major impact on the final performance of the hydropower plant [11, 13]. The RENOVHydro project relies on a systematic assessment of the hydropower plants generation increase of each possible upgrade option using the SIMSEN software as a backbone to identify the most cost-effective civil and electromechanical options. The SIMSEN simulation software enables to model an entire hydro power plant including hydraulic, mechanical and electrical system and their related control. The numerical models enable considering various hydraulic layout configurations, including non-linear head losses, realistic empirical turbine performance hill chart, generator efficiency as well as operating flexibility offered by variable speed technology. Thus, each hydropower plant upgrade option can be assessed by considering hydraulic structure, hydro units and hydropower station interaction with the grid for the provision of ancillary services, as well.

This paper presents the methodology of the RENOVHydro project to determine the best cost-effective modernization options. The RENOVHydro methodology is illustrated on a hydropower plant test case with 80MW installed capacity and comprising 4 Francis turbines operated under a maximum head of 107mWC. Different civil and electromechanical options are compared considering the available hydrology and the electricity market for a typical year. The annual revenue, the annual energy generation and the profitability are then computed to provide the optimal renovation option. Finally, with these systematic studies adaptable to any type of hydraulic machine, the assessment of any scenario is made possible considering economical, technical and environmental aspects. This high level of support for the decision-making process drastically reduces the risks of selecting under-optimal solution.

1. Methodology to select the best technical options

The RENOVHydro project is dedicated to the renovation of an existing hydroelectric power plant and an independent assessment of a high number of civil and electromechanical potential modifications using a unique methodology. Thus, energy and economic indicators such as annual energy generation, annual amount of turbined/pumped water, energy coefficient, investment cost, profitability and ancillary services for each renovation option can be analysed to identify the technical trends according a given political, economic and environmental context. The main methodology of this systematic study is illustrated in the Fig. 1 and the workflow of the RENOVHydro project is described in Fig. 4.

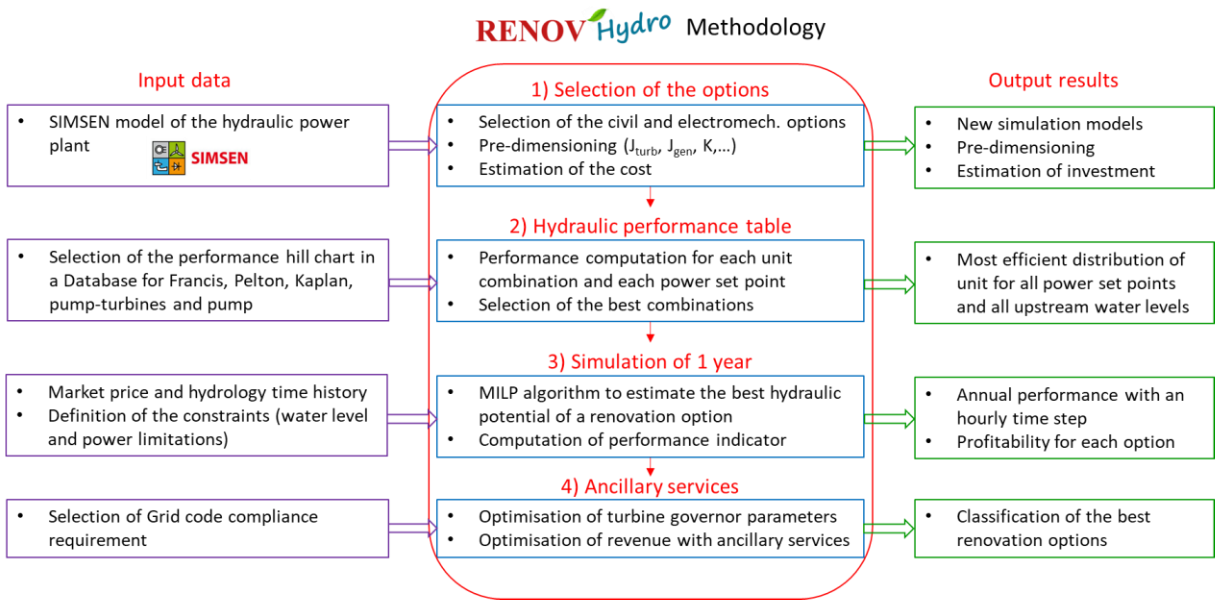


Fig. 1. Methodology of the RENOVHydro project.

1.1 Selection of the options

This first step focuses on the importation of the SIMSEN model of the original hydraulic power plant and on the selection of civil and electromechanical engineering renovation options. The SIMSEN simulation software enables to model an entire power plant including hydraulic, mechanical and electrical system and their related control systems [9, 12, 14]. Thus, the pipe frictional losses, the singular head losses and a realistic performance hill chart of the turbine are considered in the simulation. If the performance hill chart of the turbine is not known by the user, a new one can be selected in a database according to the value of the speed factor n_{ED}, the discharge factor Q_{ED} at the best efficiency point and the year of commissioning. The performance hill charts listed in the database were generated with a polynomial bi-variate functions based on Hermite polynomials [5].

$$n_{ED} = \frac{n \cdot D_{ref}}{\sqrt{gH}} \;;\; Q_{ED} = \frac{Q}{D_{ref}^{\;2} \cdot \sqrt{gH}} \;;\; T_{ED} = \frac{T}{\rho g H D_{ref}^{\;3}}$$

An example of hill chart is illustrated in Fig. 2. This performance hill chart selected in the database is compared with experimental measurement on a reduced scale model of a Francis turbine.

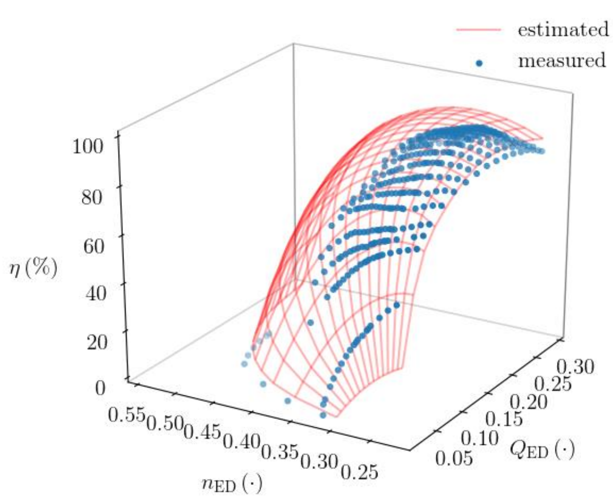


Fig. 2. Performance hill chart from the database versus experimental measurement on reduced scale model of a Francis turbine.

After selecting the reference SIMSEN model, the following renovation options are available for civil engineering and hydroelectric modifications:

- For hydraulic structure:
  - Improve the efficiency of the water intakes;
  - Increase the conveyance capacity of the waterways;
  - Increase headrace reservoir storage;
  - Decrease the head losses in the waterways (e.g. enlarge headrace, add new tunnel, add new penstock);
  - Modify the hydraulic inertia of the waterways to improve response time (e.g. surge tank volume, diaphragm);
- For hydraulic machinery:
  - Replace components such as turbine runner to increase turbine efficiency;
  - Upgrade a unit by replacing the turbine, considering also turbine type modification to increase installed capacity and increase turbine efficiency;
  - Adding a fully new unit to increase installed capacity and redundancy;
  - Add new pumping capacities for introducing/increasing storage capacity.
- For electrical equipment:
  - Increase of generator capacity to comply with turbine capacity;
  - Introduce full size frequency converter on existing unit to allow for variable speed operation and thus improve unit operating range, efficiency, flexibility, and control services especially for unit with pumping capacity;
  - Replace fixed speed generator by variable speed machine (Full Size Frequency Converter or Double Fed Induction Machine);
  - Increase available rotating inertia for improved grid stability.

After selecting the different renovation options for a given project, all possible combinations of options and the associated SIMSEN models will be automatically generated. Moreover, for each renovation option, a pre-dimensioning and a cost estimation are computed to help the user for a first selection of the most relevant renovation options.

1.1.1 Pre-dimensioning

The dimensioning of the spiral casing, the runner and the draft tube for each type of turbine (Francis, Pelton, Kaplan, pump-turbine and pump) has been determined using statistical laws [2, 3, 4, 6, 7, 10, 16, 17] requiring knowledge of only four parameters:

- Mechanical power,
- Rated head,
- Year of commissioning,
- Frequency of the electrical grid.

This first dimensioning makes it possible to define the complete geometry of a turbine (spiral case, runner, draft tube) and to estimate its rated data (rated discharge, rated rotational speed, peak efficiency, reference diameter of the runner, generator and runner inertia). All this information was validated by comparing the geometries estimated with existing hydraulic installations described in the Henry's book [8]. The maximum error found on more than 50 test cases was a maximum of 10 percent.

1.1.2 Price estimation of the modifications

The price for each electromechanical element is based on the publication from Alvarado-Ancieta [1] and requires the knowledge of the head and discharge for a unit. This current estimation of the price considers the turbine, governors, valves, cooling and drainage water systems, cranes, workshops, generators, transformers, earthing systems, control equipment, telecommunication systems and auxiliary systems (draft tube gates, heating and ventilation, domestic water and installation). The price for each type of renovation option (runner replacement, turbine replacement, unit replacement), as well as a method of estimating prices for civil engineering options will be defined in a next stage of the project.

1.2 Hydraulic performance table

For each renovation option, a hydraulic performance table is computed in order to operate the hydraulic power plant at its maximum performance for a given power set point and a given gross head. To evaluate the hydraulic power plant performances over the entire operating range, each unit combination and each guide vane opening combination are evaluated for a given upstream water level. The total number of combinations is defined by the following equation, where *n* is the maximum number of units and *p* is the number of units in operation. For instance, for a hydraulic power plant with 4 units, the number of combinations is equal to 32.

$$\text{Number of combination} = \sum_{p=1}^{n=\#Unit} \frac{n!}{p!(n-p)!} \cdot p$$

The main methodology to study the entire operating range is the following:

1. Among the different units of the power plant, <u>one unit is defined as the reference</u>. For this unit only, the guide vane opening evolves between **10 and 100% opening**.
2. For each fixed guide vane opening of the reference unit, <u>the other units in operation</u> operates jointly for guide vane opening **between 40% and 100%**. The openings below 40% are not considered because the global efficiency at partial load is significantly deteriorated. For instance, for a given power, it is more advantageous to have two units operating close to the best efficiency point (BEP) than to have three units at partial load with low efficiency.
3. For each combination of units, the hydraulic power, the discharge, the rotational speed, the guide vane opening and the net head of each unit are calculated. The global performance of the hydraulic power plant is also computed by the following equation for turbine mode, where P_m is the mechanical power, Q is the discharge and H is the gross head:

$$\eta_{global} = \frac{\sum_{i=1}^{\#Units} P_{m,i}}{\sum_{i=1}^{\#Units} \rho g Q_i H_i}$$

4. Points 1, 2 and 3 are repeated by modifying the reference unit.
5. Finally, the combination of units offering the best global efficiency for a given power set point is saved.

Using the above methodology for 4 Francis turbine units, it requires 2000 different operating conditions to be simulated to derive the hydraulic performance table for one water level in the upstream reservoir. This method is applicable to all types of machines, but it is important to note that the Pelton and Kaplan turbines have respectively the number of injectors and the blade pitch angle β as additional degree of freedom. Therefore, a pre-process is necessary to determine the best combination (injector opening – number of injectors) and (GVO – blade pitch angle). Finally, this method should be applied for different water levels of the upstream reservoir. An example of results is illustrated in Fig. 3 for a given upstream water level and a hydraulic power plant with 4 Francis turbines. With this type of information, it is interesting to note that for a power set point lower than 18MW, only unit #4 can be operated in order to have the best performance. In addition, in this figure, the global performance considering energy losses along the pipes, the efficiency of the generator and transformer and the hydraulic characteristic of each unit is indicated on the right axis.

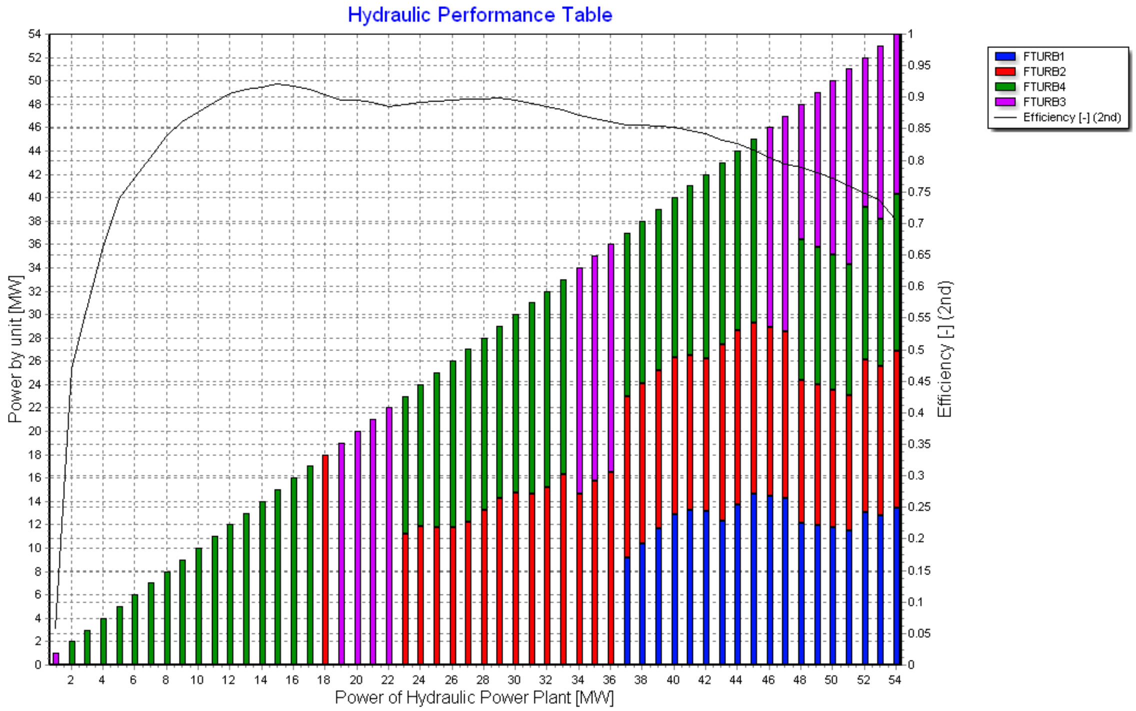


Fig. 3. Hydraulic performance table for a given upstream water level and a hydraulic power plant with 4 Francis turbines, which provides the optimal distribution of power over the 4 units for a given total power set point and a given gross head.

1.3 Simulation of an operating year

In order to simulate a complete year and compute production capacity of each renovation option, the following input data must be defined:

- The electricity market price time history and the hydrology time history for a reference year.
- Power and level limitations during a year. The following constraints can be defined by the user:
  - A minimum and maximum water elevation of the upstream reservoir.
  - A maximum power set point for the hydro power plant as function of the water level in the upstream reservoir.
  - A minimum and maximum power set point for each unit.
  - Limits of released flow according the environmental rules and laws in power.

In order to be able to compare very different technological renovation options, it is essential to systematically calculate the maximum performance (annual energy generation, annual amount of turbined/pumped water, etc.) for a reference year. To guarantee this best performance for each renovation options, a mathematical optimisation approach is used with a Mixed-Integer Linear Programming algorithm. Thus, with a reference hydrology and electricity market price time history, the algorithm optimizes the power output throughout the year to maximize revenue.

This mathematical approach has the advantage of maximizing the annual revenue (objective function), regardless of the technological option chosen. However, this type of problem requires a linearization of the auxiliary variables. For instance, the link between the total power and the total discharge defined by the hydraulic performance table is linearized with secants. The optimisation problem can be written as:

- Objective function: $\max\left(C^T x\right)$ Maximise the revenue:
- Unknown variables: x Total power of the hydraulic power plant and water level in the reservoir
- Constraints: $Ax = b$ Equality linear constraints
  $Ax < b$ Inequality linear constraints
  $I \leq x \leq U$ Bound constraints

Moreover, to save computational resource and time, the problem is formulated in two stages optimisation problem. First, the reference year is divided into shorter periods of time: 12 months. The aim of the first stage optimisation problem is to find the optimal amount of turbined water for each month. In the second stage, for each month, the hourly MILP problem is solved with respect to volume define in the first stage.

Finally, this mathematical approach makes it possible to determine energy and economic indicators such as annual energy generation, annual amount of turbined/pumped water, energy coefficient, investment cost and profitability for each renovation option. As the annual revenue has been maximized, the different technological renovation options can be analysed to identify the technical trends according a given political, economic and environmental context. This information is valuable assistance in the decision-making process regarding the economic potential of a project.

1.4 Ancillary services analysis

With transient simulations, the ancillary services and the flexibility of production is quantified and the realistic primary and secondary control potential can be assessed. The performance offered by the renovation options regarding interaction with the electrical power networks, such as primary and secondary control capabilities to determine the maximum load step response compatible with Transmission System Operator requirements, is evaluated [15]. This part of the study requires the optimization of the parameters of the power and speed regulators. This complex subject will be developed in more detail in a future stage of the project.

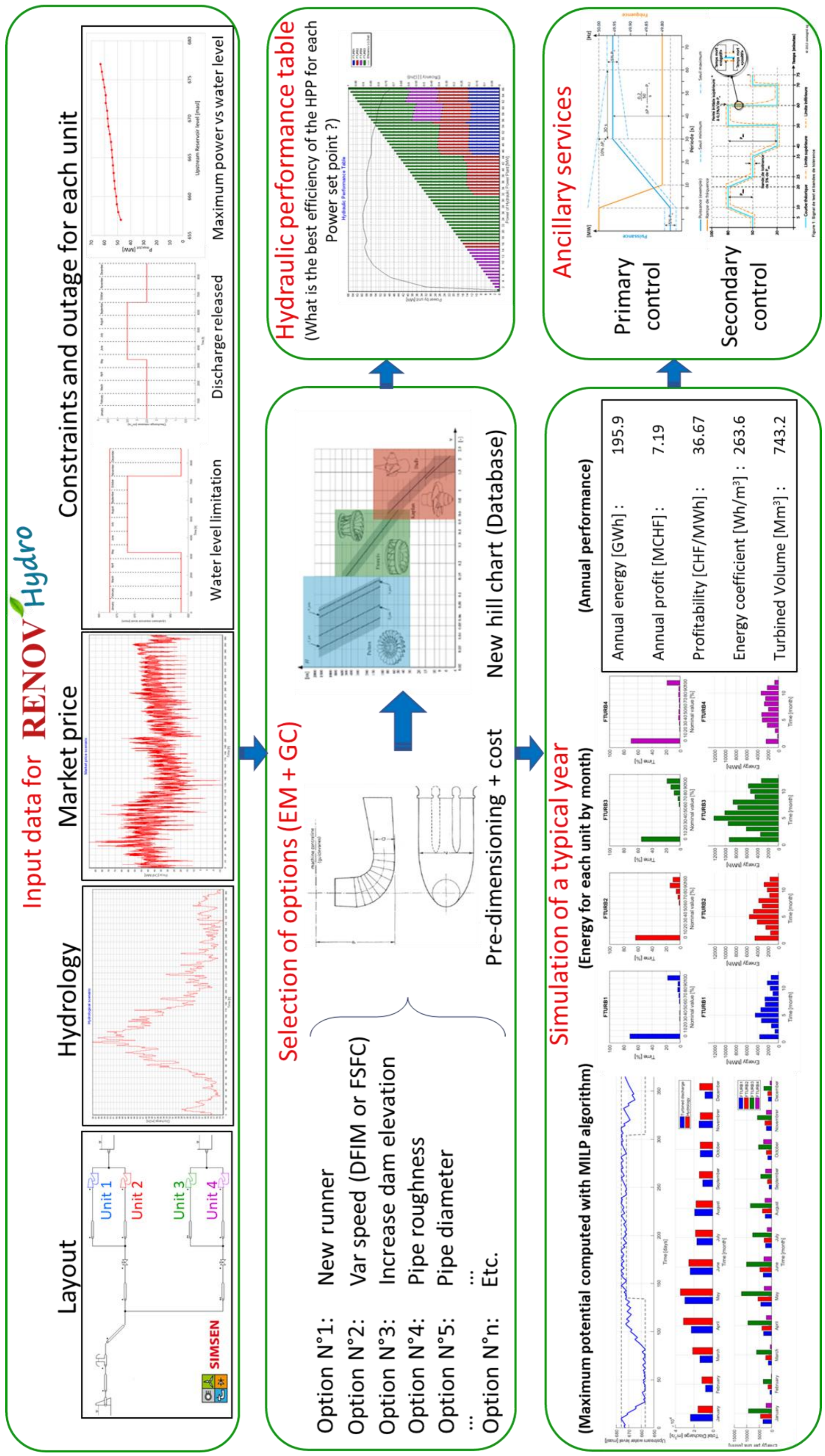
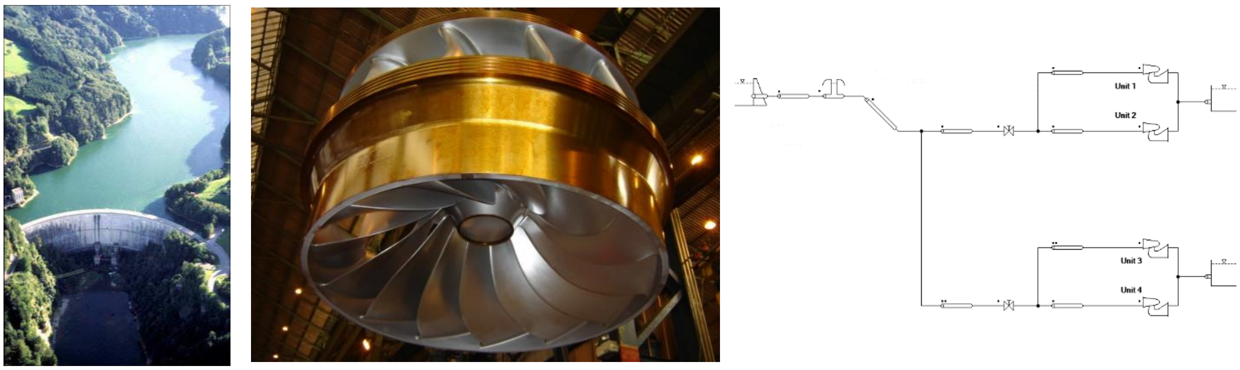


Fig. 4. Workflow of the RENOVHydro project.

2. Application of RENOVHydro methodology to a test case

The Hauterive power house was put in operation in 1902 with 8 units under a gross head of 69m. Then the dam of Rossens, see Fig. 5a, was built between 1944 and 1948 and connected to the Hauterive power station through a 6km long gallery, a surge tank with a diameter of 15m and finally a penstock with a length of 400m. The power house was then equipped with 3 Francis turbines of 15.5 MW and 2 Francis turbines of 7.5 MW under a maximum head of 110m. In 2007, the 2 small units were replaced by one 24.5 MW Francis turbine unit, see Fig. 5b. Table 1 gives the main characteristics of the 4 units today in operation [13].



a) Rossens dam *b) New Francis turbine runner of Unit #3* *c) SIMSEN model of the Hauterive power house*

Fig. 5. Picture of the Rossens dam (a), of the new Francis turbine runner of Unit #3 (b) and the SIMSEN model of the Hauterive power house (c)

Table 1 : Francis turbines nominal parameters.

	Unit #1	Unit #2	Unit #3	Unit #4
Rated Power P_n [MW]	15	15	24.5	15
Rated Discharge Q_n [m^3/s]	15	15	26	15
Rated Net Head H_n [m]	99	99	102	99
Rated rotational speed Nn [tr/min]	300	300	300	300
Reference Diameter D_{ref} [m]	1.8	1.8	1.97	1.8
Specific speed N_q [-]	37	37	47.7	37

After updating the unit #4 of the Hauterive power house, would it be economically interesting to update the other units? This case study proposes to compare the following technological options:

1. Update the 3 old units. The unit #3 is not modified. For this option, 5 rotational speed are compared: N = [300, 375, **428**, 500, 600] rpm. The inlet pipes are kept for this option.
2. Update the unit #4 and replace the two other units by only one unit of 30MW. For this new unit, the inlet pipe diameter is increased from 2.1 to 2.97m. The unit #3 is not modified. For this option, 3 rotational speed are compared: N = [250, **272**, 300] rpm.
3. Replace the 3 old units by a new one of 45MW. For this new unit, the inlet pipe diameter is increased from 2.1 to 3.64m. The unit #3 is not modified. For this option, 3 rotational speed are compared: N = [214, **230**, 250] rpm.

The rotation speeds in bold are those estimated by RENOVHydro software during the pre-dimensioning phase. The nominal net head select for all the renovation options is set to 69m which corresponds to the average net head of the units obtained from the original situation simulation of a typical year.

For each renovation option, the pre-dimensioning, the cost of a new unit, the hydraulic performance table and the performance indicators are computed and compared. For this study, the following assumptions are considered:

- The electricity market price time history corresponds to the spot price in Swiss franc in 2017 and is illustrated in Fig. 6.
- The hydrology time history corresponds to a median value over the last 10 years and is illustrated in Fig. 7.
- A minimum and maximum water level are defined for the upstream reservoir and illustrated in Fig. 8.
- A released flow in normal operating conditions is applied, see Fig. 8.
- A maximum power set point for the hydro power plant as function of the water level is defined for the upstream reservoir and is illustrated in Fig. 9.
- The costs of modifying the inlet pipes and of civil engineering are not considered.

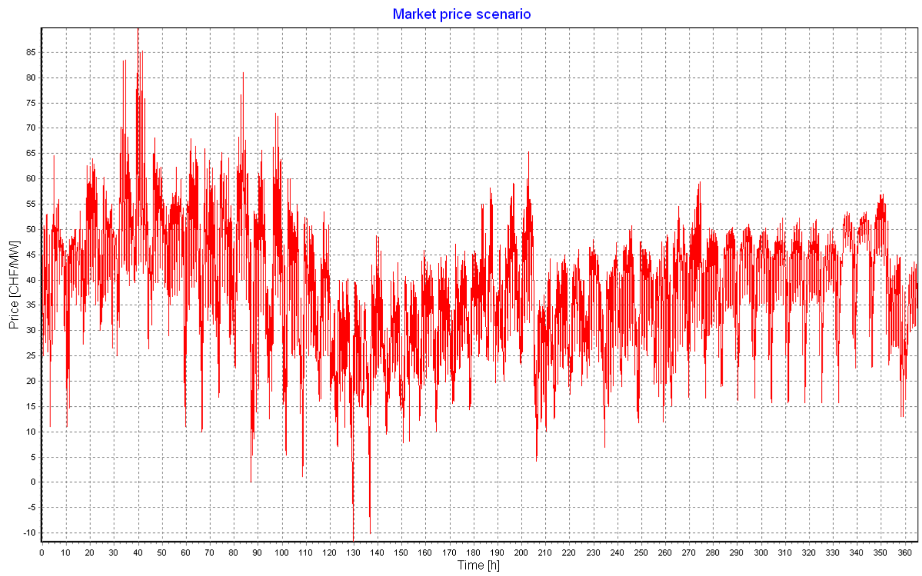


Fig. 6. Electricity market price time history corresponding to the spot price in Swiss franc in 2017.

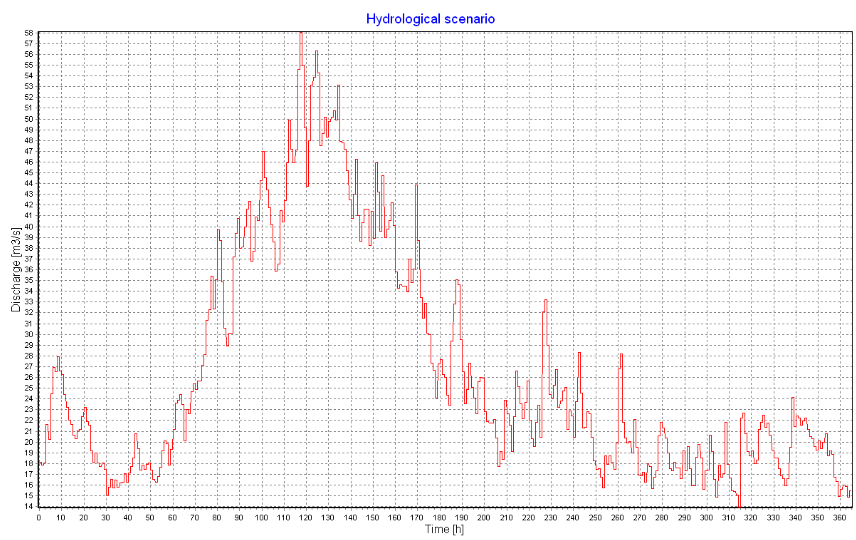


Fig. 7. Hydrology time history corresponding to a median value over the last 10 years.

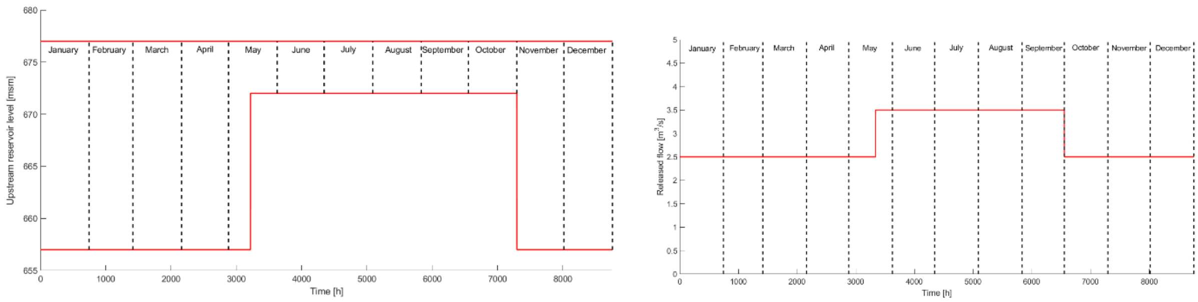


Fig. 8. Minimum and maximum water level for the upstream reservoir and released flow in normal operating conditions.

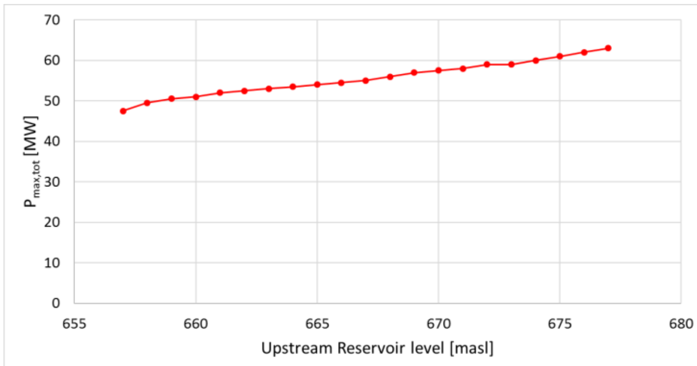


Fig. 9. A maximum power set point for the hydro power plant as function of the water level.

3. Discussion

The RENOVHydro methodology was applied to the 3 renovation options with different rotational speeds. The results for the original hydraulic power plant are first illustrated in Fig. 10 to visualize the overall behaviour of this solution.

- The Fig. 10a) defined the water level in the upstream reservoir for the reference year. This information is used to validate compliance with water level limitation constraints. In addition, the fact that the water level on January 1 corresponds to the level on December 31 ensures that the power produced throughout the year is obtained only with hydrology. Finally, between January and March, the water level can drop to its minimum level because a high hydrology is expected from the beginning of April.
- The ratio between the turbined water volume and the hydrology input volume is shown in Fig. 10b). This information is related to the evolution of the water level and validates that the turbined flow corresponds to the inflow received by the hydrology over the entire year.
- The Fig. 10c) shows the energy produced by each turbine, each month of the year. For the original hydraulic power plant, only unit #3 has been updated and therefore has a higher peak efficiency than the other units (see Table 2). Thus, unit #3 produces most of the energy over the year and the other units are in operation only to produce the maximum total power of the hydraulic power plant.
- The distribution of operating time by power set point and the energy produced by each unit for each month is illustrated in Fig. 11. It is interesting to note that the units are operated mostly at a power set point greater than 80% of their maximum power as they operate closer to their best efficiency point. Finally, over the year, the units are standstill more than 55% of the time.

In order to compare the different renovation options, a summary table showing annual revenue, annual production and profitability is illustrated in Table 2. These values have been weighted by the values of the original layout (Annual revenue = 7.19MCHF, Annual production = 196GWh and Profitability = 36.7CHF/MWh). A comparison of these economic indicators with the actual values validated these results. The price of a unit renovation is also indicated in the table and is weighted by the price for upgraded unit #1 (CHF 8.4 million) with the same rotation speed as originally. The most relevant results are:

- By comparing the different rotational speeds, we can see that the efficiency of the new units is better for specific speeds N_q close to 40. Therefore, low rotational speeds are preferable. However, it is important to note that the function between peak efficiency and N_q has an optimal value and that the rotational speed should not be too low.
- The highest revenue is obtained with the renovation option 1, i.e. with the update of the 3 units with a rotation speed of 300 rpm.
- The global efficiency of the power plant obtained with the hydraulic performance tables is illustrated in Fig. 12 for each renovation option with the lowest rotational speed. For the total power range, the best efficiency is obtained for the renovation option 1 with 4 units. Thus, the higher the number of units, the better the power range is covered. In addition, it is interesting to note that the efficiency of the power plant is identical for power set points between 21MW and 30MW. This power range is covered by unit # 3 only. As this unit is common to all renovation options, the efficiency in this power range corresponds to the efficiency of unit #3 alone.
- The maximum revenue generated by each renovation option is obtained for renovation option 1 with a rotational speed N = 300rpm. This conclusion is consistent with the best efficiency of the hydraulic power plant. Moreover, only this solution allows to have a higher revenue than the current one.
- The cost of each unit increases with the reference diameter. Despite the fact that the upgrade of the 3 units increases the annual production, the cost of 3x15MW units is 9.9% higher than the cost of 1x15MW and 1x30MW unit and 11% higher than the cost of 1x45MW unit. However, having 4 units is a good solution for maintenance period because the power range will be better covered. Therefore, the best economic option shall be carefully evaluated considering maintenance periods and possible outage over the whole concession duration. The consideration of these maintenance periods in the economic calculation will also be included in a future stage of the RENOVHydro project.

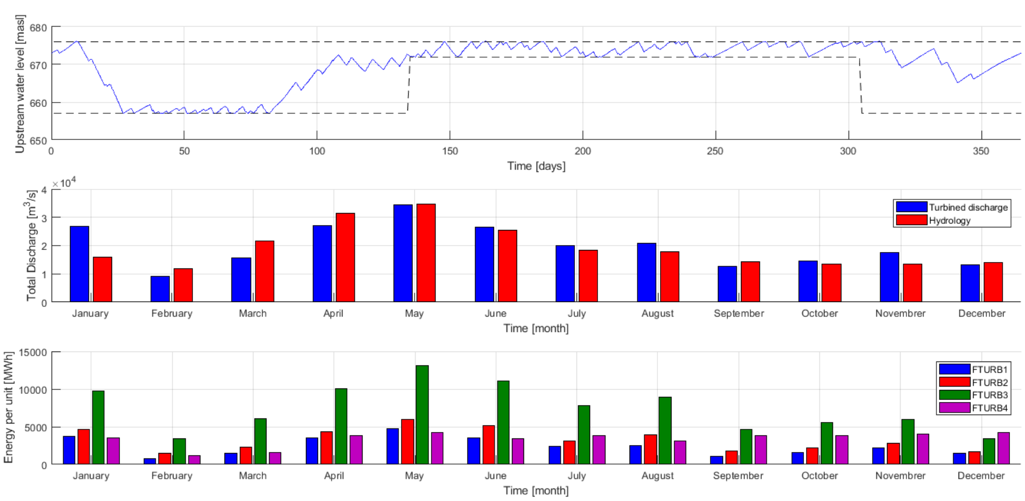


Fig. 10. Annual simulation results for the original situation:
a) water level in the upstream reservoir for each hour,
b) sum of the turbined flow and the hydrology for each month,
c) energy produced by each unit for each month.

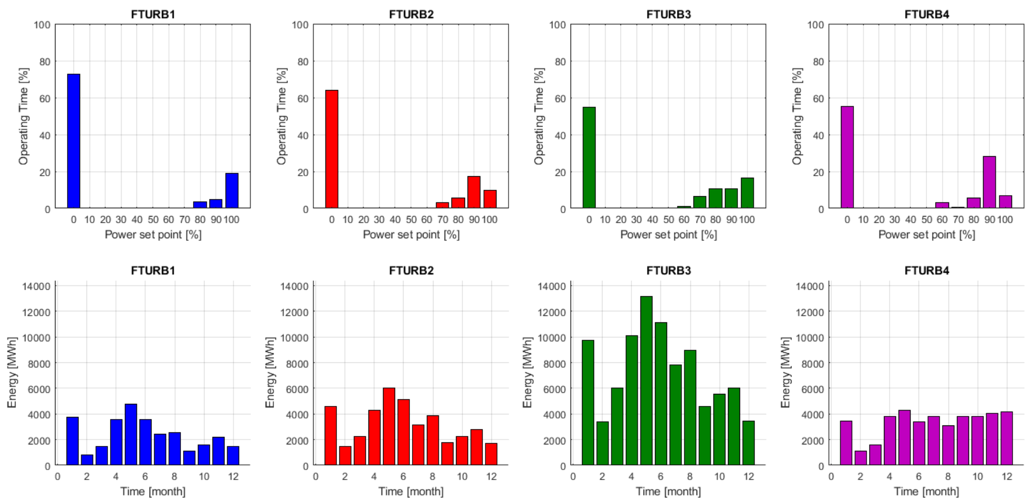


Fig. 11. Annual simulation results for the original situation:
a) distribution of operating time by power set point.
b) energy produced by each unit for each month.

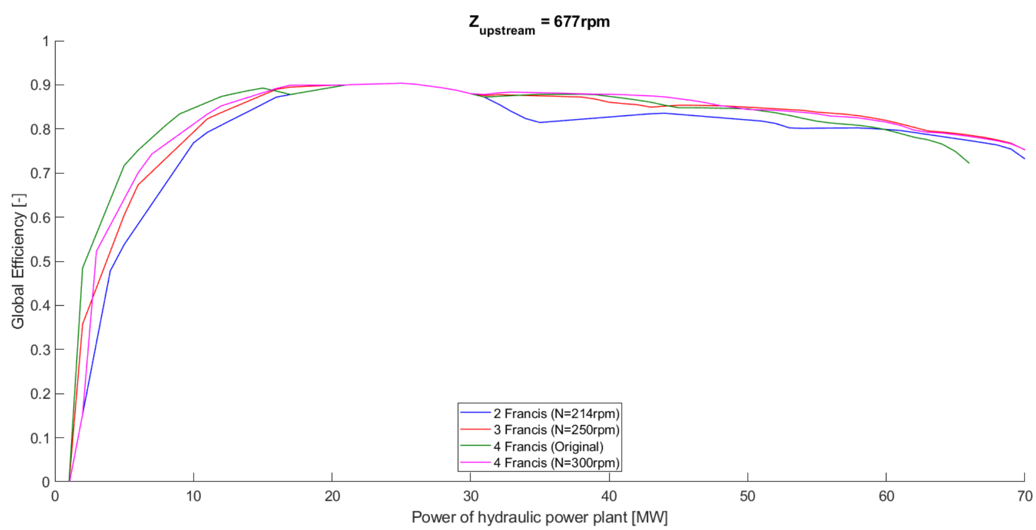


Fig. 12. Global efficiency for each renovation option with the lower rotational speed. The water level of the upstream reservoir is equal to 677 masl.

Table 2 : Comparison between the renovation options.

Scenarios	Name turbine	P [MW]	N [rpm]	Dref [m]	Nq [-]	Eta [-]	Revenue [-]	Production [-]	Profitability [-]	Cost [-]
4 Francis (original)	FTURB1	15	300.000	1.800	47.486	0.923	1.000	1.000	1.000	0.000
	FTURB2	15	300.000	1.800	47.486	0.923				0.000
	FTURB3	25	300.000	1.972	59.475	0.951				0.000
	FTURB4	15	300.000	1.800	47.486	0.923				0.000
										0.000
4 Francis (N = 300rpm)	FTURB1	15	300.000	1.817	53.434	0.958	1.006	1.005	1.002	1.000
	FTURB2	15	300.000	1.817	53.434	0.958				1.000
	FTURB3	25	300.000	1.972	59.475	0.951				1.000
	FTURB4	15	300.000	1.817	53.434	0.958				0.000
										3.000
4 Francis (N = 375rpm)	FTURB1	15	375.000	1.651	66.898	0.955	0.997	0.996	1.001	1.002
	FTURB2	15	375.000	1.651	66.898	0.955				1.002
	FTURB3	25	300.000	1.972	59.475	0.951				1.002
	FTURB4	15	375.000	1.651	66.898	0.955				0.000
										3.007
4 Francis (N = 428rpm)	FTURB1	15	428.000	1.568	76.482	0.952	0.990	0.990	1.001	1.005
	FTURB2	15	428.000	1.568	76.482	0.952				1.005
	FTURB3	25	300.000	1.972	59.475	0.951				1.005
	FTURB4	15	428.000	1.568	76.482	0.952				0.000
										3.014
4 Francis (N = 500rpm)	FTURB1	15	500.000	1.487	89.625	0.946	0.975	0.972	1.004	1.009
	FTURB2	15	500.000	1.487	89.625	0.946				1.009
	FTURB3	25	300.000	1.972	59.475	0.951				1.009
	FTURB4	15	500.000	1.487	89.625	0.946				0.000
										3.027
4 Francis (N = 600rpm)	FTURB1	15	600.000	1.409	108.209	0.934	0.982	0.979	1.004	1.018
	FTURB2	15	600.000	1.409	108.209	0.934				1.018
	FTURB3	25	300.000	1.972	59.475	0.951				1.018
	FTURB4	15	600.000	1.409	108.209	0.934				0.000
										3.054
3 Francis (N = 250rpm)	FTURB12	30	250.000	2.389	62.941	0.959	0.993	0.993	1.001	1.732
	FTURB3	25	300.000	1.972	59.475	0.951				1.000
	FTURB4	15	428.570	1.568	76.584	0.952				0.000
										2.732
3 Francis (N = 272.72rpm)	FTURB12	30	272.727	2.306	68.717	0.958	0.993	0.992	1.001	1.734
	FTURB3	25	300.000	1.972	59.475	0.951				1.000
	FTURB4	15	428.570	1.568	76.584	0.952				0.000
										2.734
3 Francis (N = 300rpm)	FTURB12	30	300.000	2.224	75.676	0.956	0.989	0.989	1.001	1.738
	FTURB3	25	300.000	1.972	59.475	0.951				1.000
	FTURB4	15	428.570	1.568	76.584	0.952				0.000
										2.738
2 Francis (N = 214.28rpm)	FTURB124	45	214.286	2.867	66.045	0.960	0.979	0.978	1.002	2.767
	FTURB3	25	300.000	1.972	59.475	0.951				0.000
										2.767
2 Francis (N = 230.77rpm)	FTURB124	45	230.769	2.784	71.177	0.959	0.982	0.980	1.003	2.771
	FTURB3	25	300.000	1.972	59.475	0.951				0.000
										2.771
2 Francis (N = 250rpm)	FTURB124	45	250.000	2.702	77.186	0.957	0.978	0.978	1.002	2.776
	FTURB3	25	300.000	1.972	59.475	0.951				0.000
										2.776

4. Conclusion

The RENOVHydro project is dedicated to the renovation of an existing hydroelectric power plant and an independent assessment of a high number of civil and electromechanical potential modifications using a unique methodology. Thus, energy and economic indicators such as annual energy generation, annual amount of turbined/pumped water, energy coefficient, investment cost, profitability and ancillary services for each renovation option can be analysed to identify the technical trends according a given political, economic and environmental context. The RENOVHydro methodology is divided into 3 distinct parts:

- This first step focuses on the importation of the SIMSEN model of the original hydraulic power plant and on the selection of civil and electromechanical engineering renovation options. With SIMSEN simulation software, the pipe frictional losses, the singular head losses and a realistic performance hill chart of the turbine are considered in the simulation. A performance hill chart of the turbine can be selected in a database according to the value of the speed factor, the discharge factor and the year of commissioning. After selecting the reference numerical model, civil engineering and hydroelectric renovation options can be selected. According to the options, the pre-dimensioning of the spiral casing, the runner and the draft tube for each type of turbine (Francis, Pelton, Kaplan, pump-turbine and pump) are determined using statistical laws. The price for each electromechanical element is also estimated. Finally, a method of estimating prices for civil engineering options will be defined in a future stage of the project.

- For the second step, a hydraulic performance table is computed for each renovation option in order to operate the hydraulic power plant at its maximum performance for a given power set point and a given upstream water level. To evaluate the hydraulic power plant performances over the entire operating range, each unit combination and each guide vane opening combination are evaluated.

- The simulation of a complete year is developed in the third part of the RENOVHydro methodology. To compute production capacity of each renovation option, the electricity market price time history, the hydrology time history, the power and water level limitations are required. To guarantee the best performance of each renovation options, a mathematical optimisation approach is used with a Mixed-Integer Linear Programming algorithm to maximize the annual revenue.

This RENOVHydro methodology was illustrated on a hydropower plant test case with 80MW installed capacity and comprising 4 Francis turbines operated under a maximum head of 107mWC. This case study proposes to compare 3 different renovation options: 1) upgrade 3 old units, 2) upgrade one unit and replace the two others old units by a new one and 3) replace 3 old units by only one. The energy and economic indicators lead to the following conclusion:

- The maximum revenue generated is obtained with renovation option 1) and a rotational speed N = 300rpm.

- For the total power range, the best efficiency is obtained for the renovation option 1). Thus, the higher the number of units, the better the power range is covered.

- Despite the fact that the upgrade of the 3 units increases the annual production, the cost of 3x15MW units is higher than the cost of 1x15MW and 1x30MW unit and the cost of 1x45MW unit. Therefore, over 50 years, it becomes advantageous to choose a solution with only 3 units, because the initial investment will be amortized faster with this renovation solution.

This first analysis indicates that option 1) produces a higher annual revenue +0.6% and option 2) is significantly cheaper –9% for a slightly lower annual revenue. This systematic study of the various technological solutions made it possible to identify the most relevant renovation options. Moreover, the best economic option shall be carefully evaluated considering maintenance periods and possible outage over the whole concession duration. The inclusion of maintenance periods in the methodology and the study of ancillary services are tools that will be added soon and that will help to select the most advantageous technological solution.

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6. Nomenclature

D_{ref}	Reference diameter [m]	n	Maximum number of units [-]	P_m	Mechanical power [W]
g	Gravity [m/s^2]	N	Rotational speed [rpm]	Q	Discharge [m^3/s]
H_n	Rated head [mWC]	p	Number of units in operation [-]	ρ	Density [kg/m^3]

Specific speed $N_q = \dfrac{N_n (Q_n)^{1/2}}{(H_n)^{3/4}}$,

IEC speed factor $n_{ED} = \dfrac{n \cdot D_{ref}}{\sqrt{gH}}$,

IEC Discharge factor $Q_{ED} = \dfrac{Q}{{D_{ref}}^2 \cdot \sqrt{gH}}$,

IEC Torque factor $T_{ED} = \dfrac{T}{\rho g H {D_{ref}}^3}$.

References

1. **Alvarado-Ancieta, C.**, "Project finance: Estimating the costs of E&M equipment", *Water Power & Dam construction*, February 2009.
2. **De Siervo, F. and de Leva, F.**, "Modern trends in selecting and designing Francis turbines", *Water Power & Dam Construction*, August 1976.
3. **De Siervo, F. and de Leva, F.**, "Modern trends in selecting and designing Kaplan turbines", *Water Power & Dam Construction*, December 1977.
4. **De Siervo, F. and Lugaresi, A.**, "Modern trends in selecting and designing Pelton turbines", *Water Power & Dam Construction*, December 1978.
5. **Gomes Pereira Junior J., L. Andolfatto and F. Avellan. "**Monitoring a Francis Turbine Operating Conditions", *Flow Measurement and Instrumentation Journal*, 2018.
6. **Gordon, J.L**., "Hydraulic turbine efficiency", *Canadian Journal of Civil Engineering* 28: 238–253, 2001.
7. **Graeser, J.-E.**, "Abaque pour pompes et pompes-turbines réversibles", *École polytechnique fédérale de Lausanne, Institut de machines hydrauliques*, Lausanne, 1978.
8. **Henry, P.**, "Turbomachines hydrauliques », *Presses polytechniques et universitaires romandes*, 1992
9. **Landry, C.**, "Hydroacoustic Modeling of a Cavitation Vortex Rope for a Francis Turbine", *EPFL Doctoral Thesis N°6547*, 2015.
10. **Lugaresi, A. and Mass, A.**, "Designing Francis turbines: trends in the last decade", *Water Power & Dam Construction*, November 1987.
11. **Maruzewski P., Rogeaux C. and Laurier P.**, "Unit-sizing of hydro power plant", *IOP Conf. Series: Earth and Environmental*, Science 15 052004, 2012.
12. **Nicolet, C.**, "Hydroacoustic Modeling and Numerical Simulation of Unsteady Operation of Hydroelectric Systems", *EPFL Doctoral Thesis N°3751*., 2007.
13. **Nicolet, C., Bollaert, E.F.R., Allenbach, P. and Gal, A.**, "Optimization of hydropower production using detailed simulation model", *Hydropower & dams*, Issue 9, 2009.
14. **Sapin, A.**, "Logiciel modulaire pour la simulation et l'étude des systèmes d'entraînement et des réseaux électriques." *EPFL Doctoral Thesis N° 1346*, 1995.
15. **Scherer, M., Schlipf, D. and Sattinger, W.,** "Test for primary control capability", Swissgrid, Version 1.1, April 2011.
16. **Schweiger, F. and Gregori, J.**, "Developments in pump-turbines", *Water Power & Dam construction*, October 1982.
17. **Schweiger, F. and Gregori, J.**, "Developments in the design of bulb turbines", *Water Power & Dam construction*, September 1988.

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