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RENOVHydro: Development of a Decision-Making Assistant for Hydropower Project Potential Evaluation and Optimization

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Zusammenfassung

Bei der Modernisierung eines Wasserkraftwerks müssen eine grosse Anzahl an Renovierungsmöglichkeiten verschiedener wissenschaftlicher Disziplinen berücksichtigt werden. Jede Entscheidung ab Projektbeginn hat einen grossen Einfluss auf die endgültige Leistung des Wasserkraftwerkes. Die RENOVHYDRO Methode evaluiert die verschiedenen Renovierungsmöglichkeiten systematisch und berücksichtigt dabei der Wasserbau, die verschiedenen Produktionseinheiten und die Interaction des Wasserkraftwerkes mit dem Stromnetz für die Bereitstellung von Netzdienstleistungen. Diese systematische Analyse ist eine wertvolle Unterstützung um Entscheidungen zu treffen und reduziert dabei drastisch die Risiken eine nicht optimale Lösung herauszufinden.

Résumé

La modernisation d'une centrale hydraulique implique d'évaluer un grand nombre d'options de rénovation dans des domaines scientifiques très différents. Dès le début du projet, chaque prise de décision a un impact majeur sur la performance finale de l'aménagement. Le projet RENOVHydro repose sur une évaluation systématique des différentes options de rénovation, en tenant compte du circuit hydraulique, des différentes unités de production et de l'interaction de la centrale hydroélectrique avec le réseau électrique afin de garantir les services au réseau. Cette analyse systématique dans le processus décisionnel réduit considérablement les risques de choisir une option de rénovation sous-optimale.

Summary

The decision-making process for the modernization of hydraulic power plant involves to overcome huge number of possible renovation options at early design stages, when each decision has a major impact on the final performance of the hydropower plant. The RENOVHydro project rely on a systematic assessment of renovation options, considering hydraulic structure, hydro units and hydropower station interaction with the grid for the provision of ancillary services. This high level of support for the decision-making process drastically reduces the risks of selecting under-optimal solution.

Main findings

- Systematic assessment process to objectively compare different renovation options.
- Complete modeling of the hydraulic power plant considering realistic performance hill chart of the hydraulic turbine, singular and regular head losses, generator and transformer efficiency, …
- Computation of energy and economic indicators to compare the different renovation options.
- Assessment of realistic primary and secondary control potential.

Contents

Abbreviations

BEP	Best Efficiency Point
ESD	Emergency Shut Down
GVO	Guide vane opening
LMH	Laboratory for Hydraulic Machines
MILP	Mixed Integer Linear Program
SFOE	Swiss Federal Office of Energy

1 Introduction

1.1 Background information and current situation

The Swiss Federal Council Energy Strategy 2050 focuses on balanced utilization of hydropower potentials and new renewable energy sources to cope with nuclear energy phasing out. According to available SFOE statistics, the nuclear power plant accounts for 36% of electricity production in Switzerland, see Figure 1. With the energy strategy 2050, the nuclear energy must be replaced by development of hydraulic and other renewable energy sources, while improving the energy efficiency of buildings.

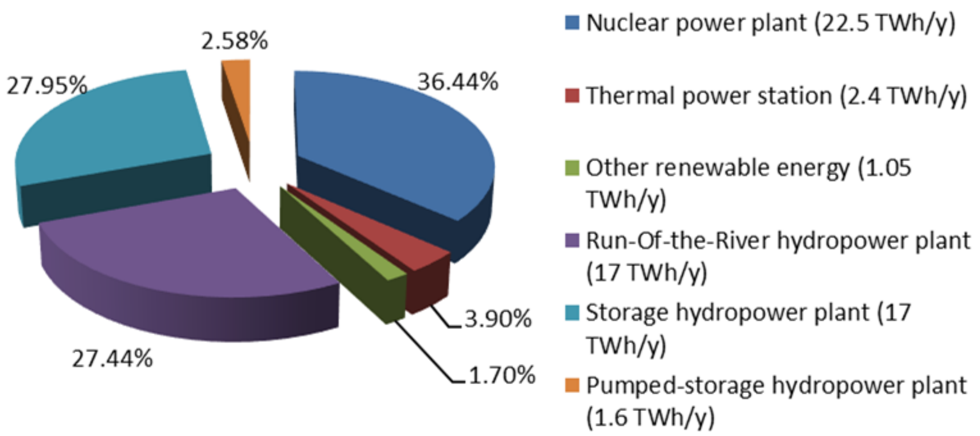


Figure 1: Electricity Generation Mix in Switzerland [2]

Moreover, 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. However, high environmental expectations restrict the perspectives of developing new large hydropower plant schemes. An optimal exploitation of the potential from the already existing facilities is therefore crucial to achieve the objectives of the Energy Strategy 2050. The production capacity potential must be addressed together with the ancillary services capacity to ensure the stability of the electrical grid. It will require some modernizations of the installation and the use of state-of-the-art technologies.

Meanwhile, a large amount of hydraulic concessions will end in the coming years, as shown in Figure 2. For each of them, stakeholders will have to estimate the true potential of a refurbished installation before committing for a new concession and long-term investments. Currently, the potential indicated by the Swiss Federal Office of Energy (SFOE) derives from Canton estimates. These estimates are performed separately for each field of engineering and it is therefore difficult to have a global vision of the necessary costs for the renovation of hydraulic power plant. Moreover, the combinatorial resulting from several possible choices in each engineering field leads to a large number of scenarios from which to estimate the potential. This cannot be achieved manually and the scenarios to evaluate must currently be selected *a priori*.

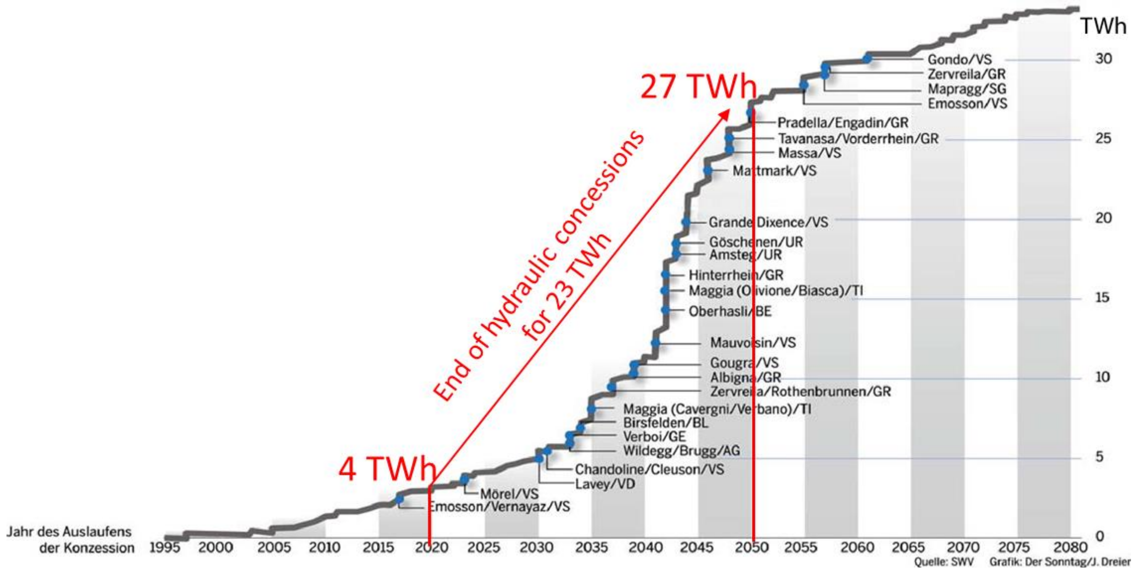


Figure 2: End of hydraulic concessions until 2080 (cumulative curve of annual productions).

By optimizing the exploitation of already existing hydropower plants, through modernization and use of state-of-the-art technologies, hydroelectric power plants could produce 870 GWh/y more by 2050, see Figure 3. This estimate takes into account the legal, economic and socio-economic constraints that currently prevail (Current conditions). This estimate may reach 1530 GWh/y if a change in economic and socioeconomic conditions is envisaged, while respecting the requirements of sustainable development and environmental protection (Optimized conditions).

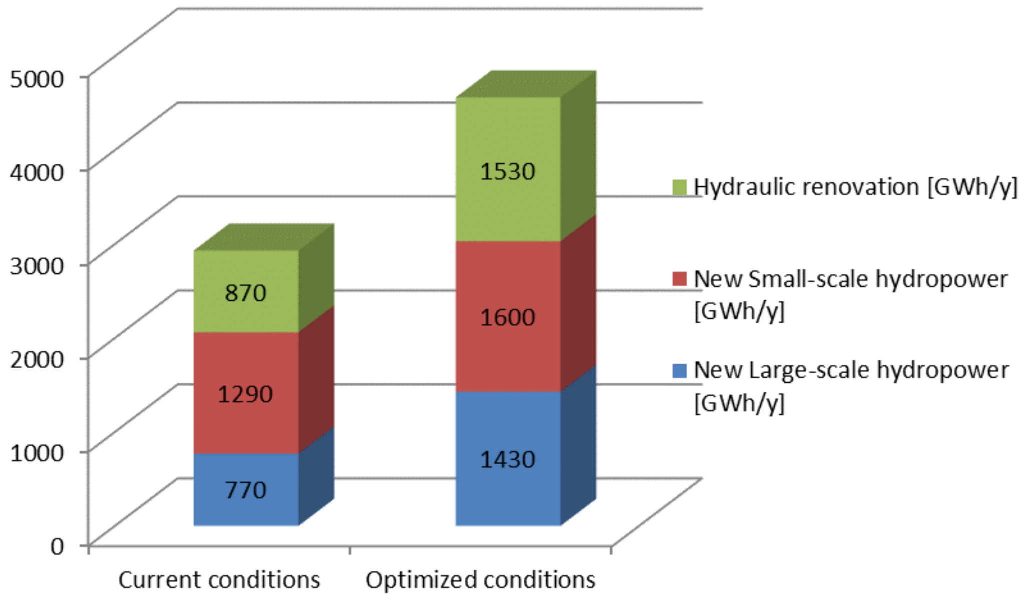


Figure 3: Estimated additional hydroelectric potential in 2050 [21]

The renovation of hydroelectric power plant is multidimensional decision-making process made-up of a number of aspects at different levels such economic and technical:

I. civil engineering work such as dam elevation, new storage capacity, new galleries or penstocks,

II. electromechanical solutions such as new turbine runner, new turbine, new pumping capacity as well as variable speed technologies,

III. environmental constraints in compliance with the Waters Protection Act,

IV. ancillary services capability.

Each decision has a major impact on the final performance of the hydropower plant after renovation and on its cost-effectiveness. To overcome huge number of renovation options of hydropower plant with a systematic approach and to support the decision-making process, the RENOVHydro library of the SIMSEN Software was developed.

1.2 Purpose of the project

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 [18, 20]. 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, see Figure 4. 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 with performance indicators such as annual energy, annual revenue, profitability, by considering hydraulic structure, hydro units and hydropower station interaction with the grid for the provision of ancillary services, as well.

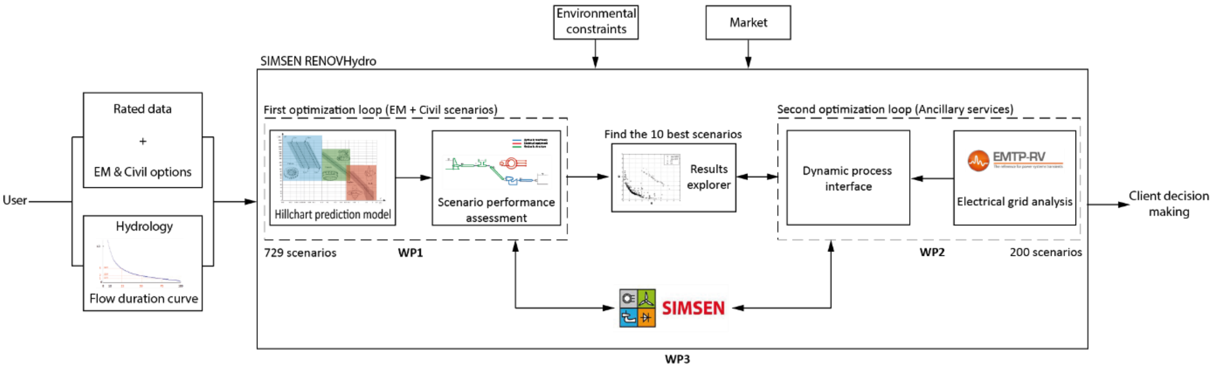


Figure 4 Flowchart of the RENOVHydro project.

Finally, this project has the advantage of combining several specialists in the hydroelectric field. **Power Vision Engineering Sàrl** has the skills in modeling, simulation and analysis of hydropower plants operation with multi-disciplinary approaches by using the SIMSEN software, widely used by large hydroelectricity companies. **EPFL-LMH laboratory** has acquired a well-known reputation of independent expertise in the field of experimental validation of hydraulic performances of reduced physical scale model of turbines, pumps and pump-turbines. The **Power Utilities** provide real test cases of Swiss hydropower plants as well as electricity market and hydrology competences to establish and validate the methodologies. Such synergies provide a high agility and have a real advantage. Finally, the proposed project allows to improve the quality of consulting engineering services regarding the provision of ancillary services, what is currently one of the best ways to achieve and secure profitable exploitation of hydropower plants in the coming years.

1.3 Objectives

To improve the productivity of a single existing hydroelectric plant, many alternative scenarios can be considered. By replacing components such as turbine runner to increase turbine efficiency, adding a fully new unit to increase installed capacity or adding new pumping capacities for introducing/increasing storage capacity, for instance 27 electromechanical options can be tested. For the civil engineering options, considering adding new galleries to increase the discharge capacity of the waterways, increasing dam reservoir storage or applying performant painting or coating on gallery or penstock inner surface to reduce head losses, for example 27 other new options must be taken into account. Thus, to model these 729 different renovation options with SIMSEN software, create the performance hill chart of the new turbines and gather the hydrology data, 9 days are necessary for a skilled staff. Moreover, assuming one hour of work to study the relevance of each case, 91 days are necessary to define the 10 best renovation options.

In addition, for a new power plant or a power plant with a power upgrade of 10%, a Grid Code requirement shall be applied. Thus, a list of forms, such as voltage stability in case of small perturbation, stability in case of short-circuit or frequency primary or secondary control capacity, must be delivered to demonstrate its compliance to Transmission System Operator requirements (Grid Code Compliance Assessment). Therefore, 10 new electrical scenarios have to be simulated for two different configurations and for each 10 best renovation options. Among these 200 new cases, each renovation option requires 4 hours of time simulations and analyses. Finally, 100 additional days are needed to define the best scenario to improve the productivity of an existing hydroelectric plant.

Therefore, a skilled and experienced engineer would need 200 days to simulate all alternative scenarios and analyze the results. This time-consuming approach would require rigor in the analysis, skills in the field of Civil, Mechanical and Electrical Engineering and the knowledge of different specific computer software, such as EMTP-RV, SIMSEN, Matlab, etc. However, currently, an engineer cannot spend as much time on a single case study. His experience guides him towards some solutions rather than others. Thus, the arbitrary choice of the most attractive scenarios and the difficulty of finding the necessary information to create an accurate performance hill chart reduces the accuracy of this manual approach.

The systematic approach proposed by the RENOVHydro project aims to significantly reduce the consuming time to study the different renovation options by a factor 20 using the following technologies:

- An input data management Graphical User Interface (GUI) guides the user in providing a formal specification of the electromechanical and civil engineering options, their associated cost, the rated data, the environmental constraints and the operational constraints associated with the hydro power project. With a knowledge-based inference model capable of generating empirical hill chart for a hydraulic machine according to the rated characteristics of the power plant, the preparation time of the different renovation options is reduced to 1 hour instead of 9 days for a project with 729 different renovation options, see Figure 5.

- In order to be able to compare very different technological renovation options, it is essential to systematically calculate the maximum performance of the hydro power plant. An automatic management of the SIMSEN models simplifies the determination of the best performance of the hydraulic power plant for a given power set point. Then, a mathematical optimization approach is used with a Mixed-Integer Linear Programming algorithm to optimize the power output throughout the year and maximize the annual revenue. This mathematical approach has the advantage of maximizing the annual revenue (objective function), regardless of the technological option chosen. Finally, a Result Explorer helps to compare the different renovation options with performance indicators to identify the best cost-effectiveness trades-off. All these new automatic tools reduced the consuming time to 3 days instead of 91 days for a project with 729 different renovation options, see Figure 5.

- With transient simulations, the ancillary services and the flexibility of production is quantified and the realistic primary and secondary control potential can be assessed. In order to automatically assess the primary control potential of the renovated hydroelectric power plant, a simple and robust methodology to deduce the parameters of a PID controller were developed. This simulation tool leads to the evaluations of the Transmission System Operator requirements for the 10 best scenarios in 7 days instead of 100 days for a project with 729 different renovation options, see Figure 5. Finally, with the FMI co-simulation protocol implementation in the RENOVHydro library, co-simulations between SIMSEN and EMTP-RV can be performed to simulate detailed hydro units in SIMSEN with a detailed transmission line and grid in EMTP-RV.

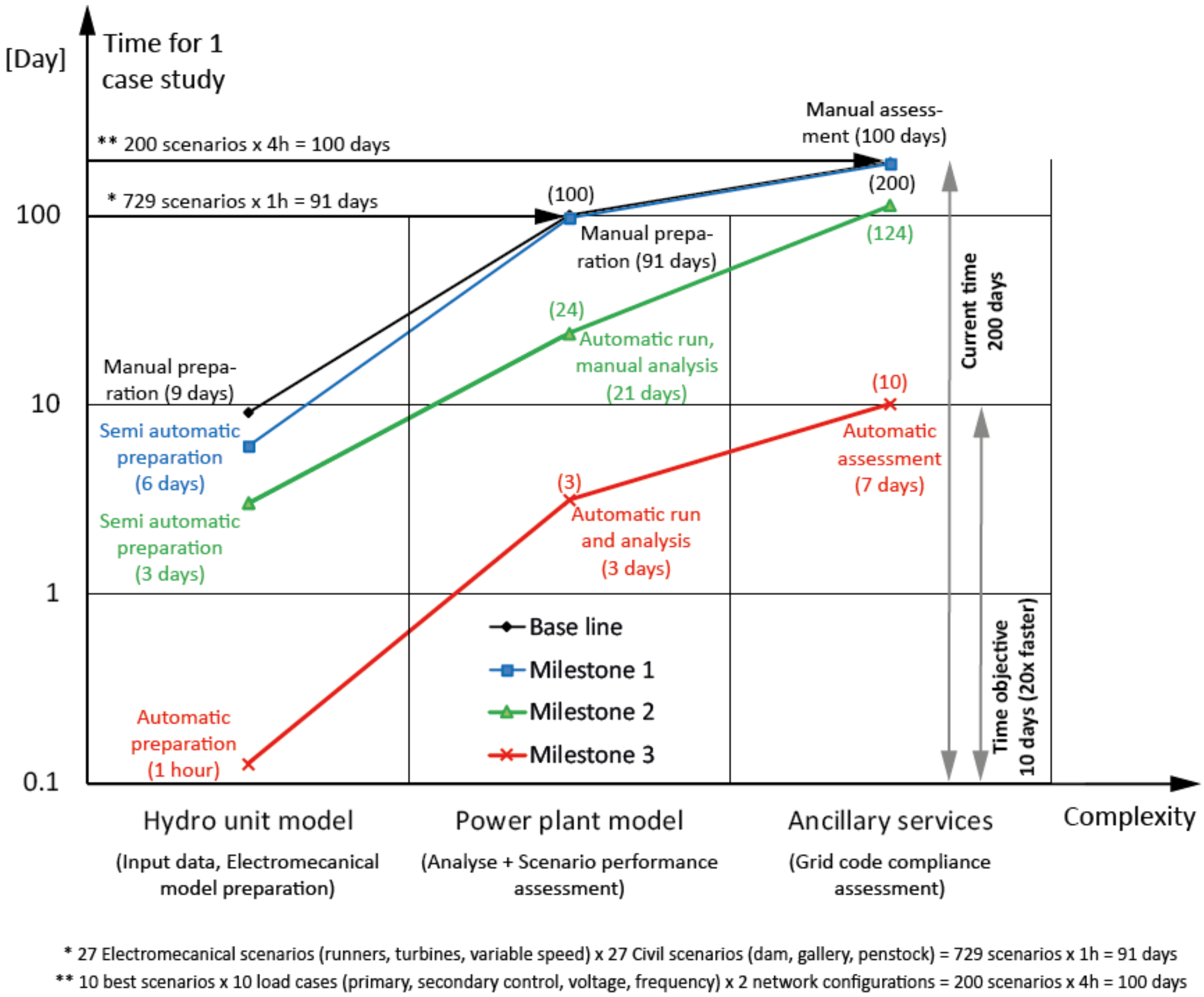


Figure 5 Time necessary to study 729 different renovation options.

2 Procedures and methodology

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, return on investment and ancillary services for each renovation option can be analyzed to identify the technical trends according to a given political, economic and environmental context. The main methodology of this systematic study is illustrated in the Figure 6 and the workflow of the RENOVHydro project is described in Figure 17.

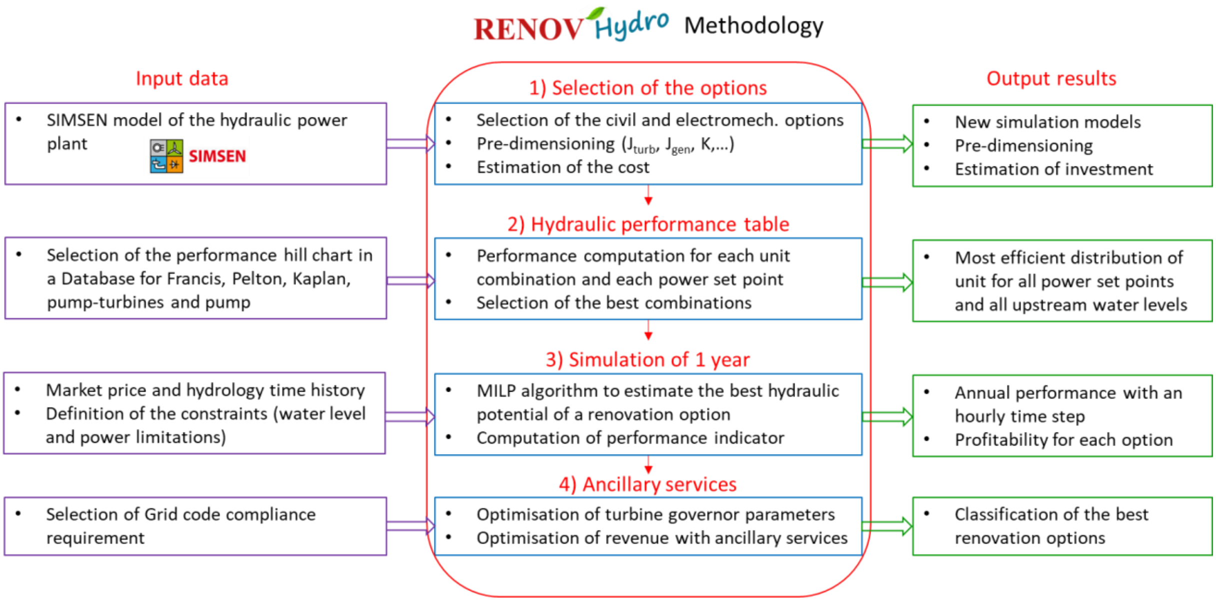


Figure 6 Methodology of the RENOVHydro project.

2.1 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, see Figure 9. The SIMSEN simulation software enables to model an entire power plant including hydraulic, mechanical and electrical system and their related control systems [14, 19, 22]. 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 [9,10].

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

An example of hill chart is illustrated in Figure 7. This performance hill chart selected in the database is compared with experimental measurement on a reduced scale model of a Francis turbine. **A validation of the database for the 3 types of turbines (Francis, Pelton and pump-turbines) are described in Section 4.1.**

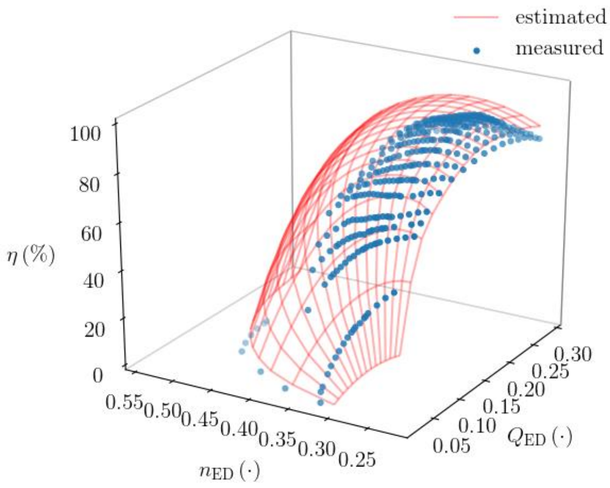


Figure 7 Performance hill chart from the database versus experimental measurement on reduced scale model of a Francis turbine.

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

- 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, see Figure 8.

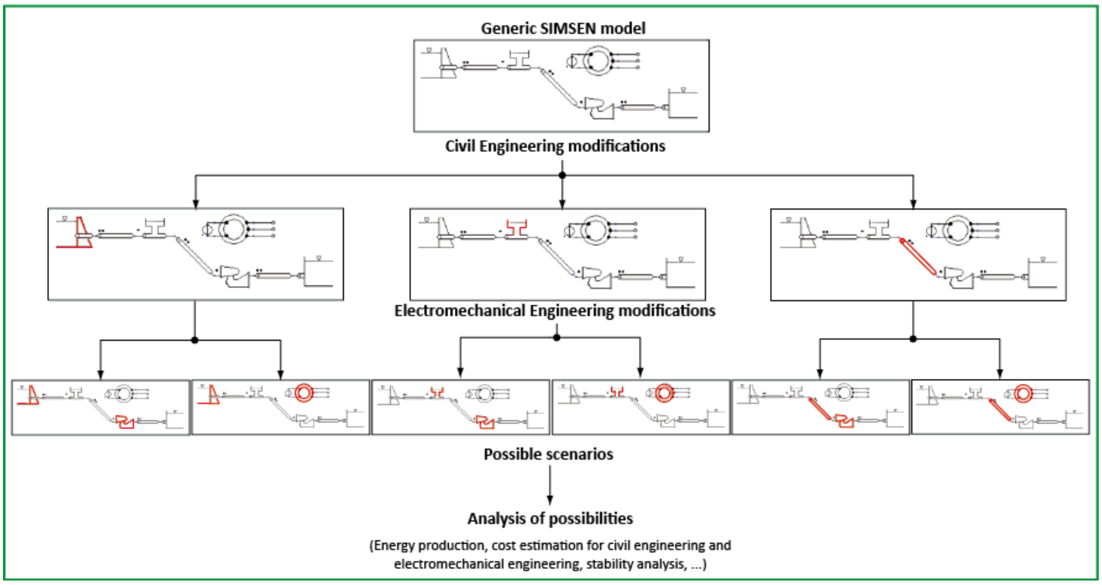


Figure 8 Block diagram of the methodology proposed in the RENOVHydro project.

Moreover, for each renovation option, a specification and a cost estimation are computed to help the user for a first selection of the most relevant renovation options, see Figure 9.

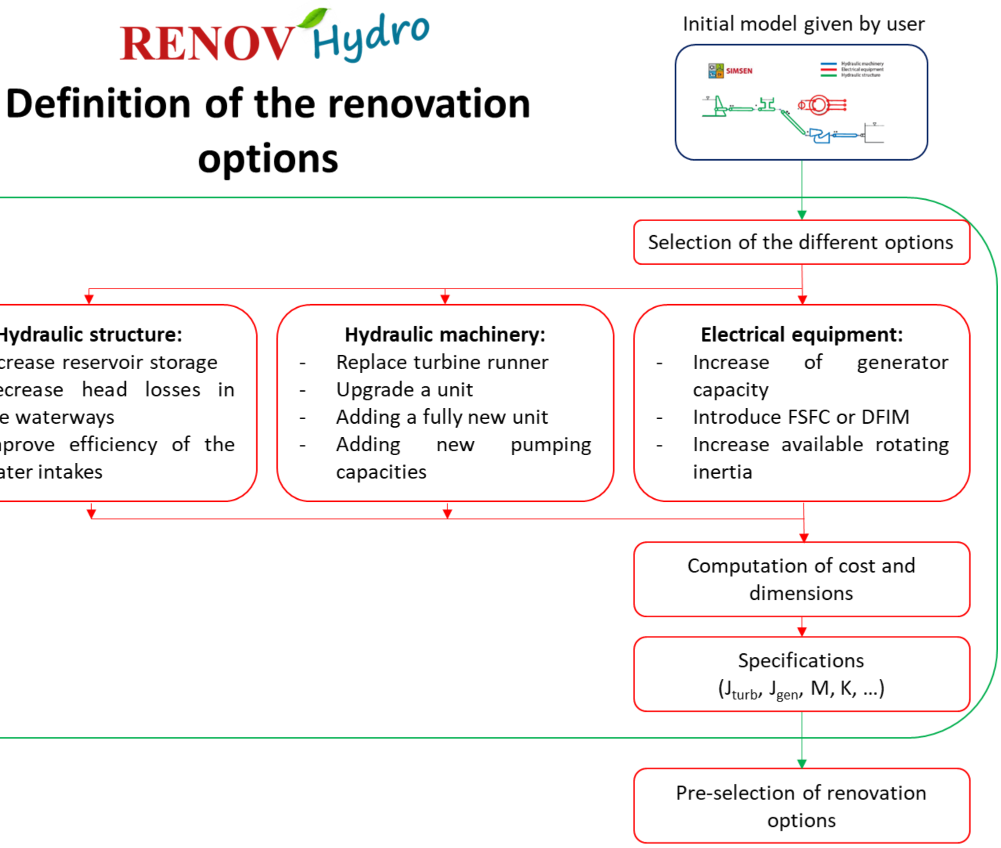


Figure 9 Detailed flowchart for the selection of the renovation options.

2.2 Specification

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 [4, 5, 6, 11, 12, 17, 26, 27] 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 [13]. The maximum error found on more than 50 test cases was a maximum of 10 percent.**

2.3 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 are also available in the RENOVHydro library.

2.4 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, see Figure 10.

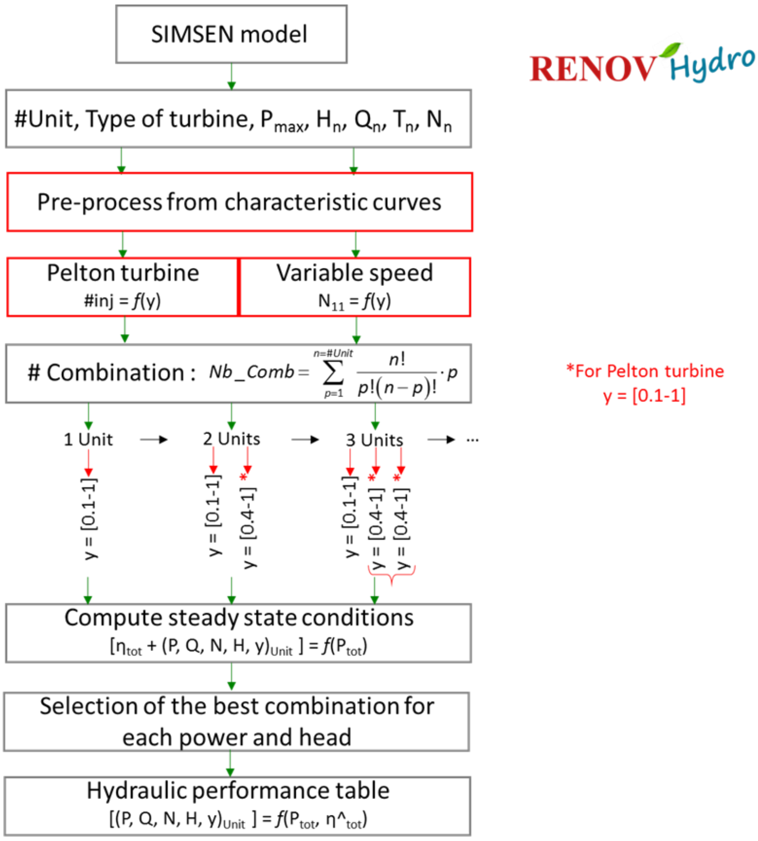


Figure 10 Detailed flowchart for the computation of the hydraulic performance table.

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, one unit is defined as the reference. 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, the other units in operation 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 to different water levels of the upstream reservoir. An example of results is illustrated in Figure 11 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 20 MW, 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.

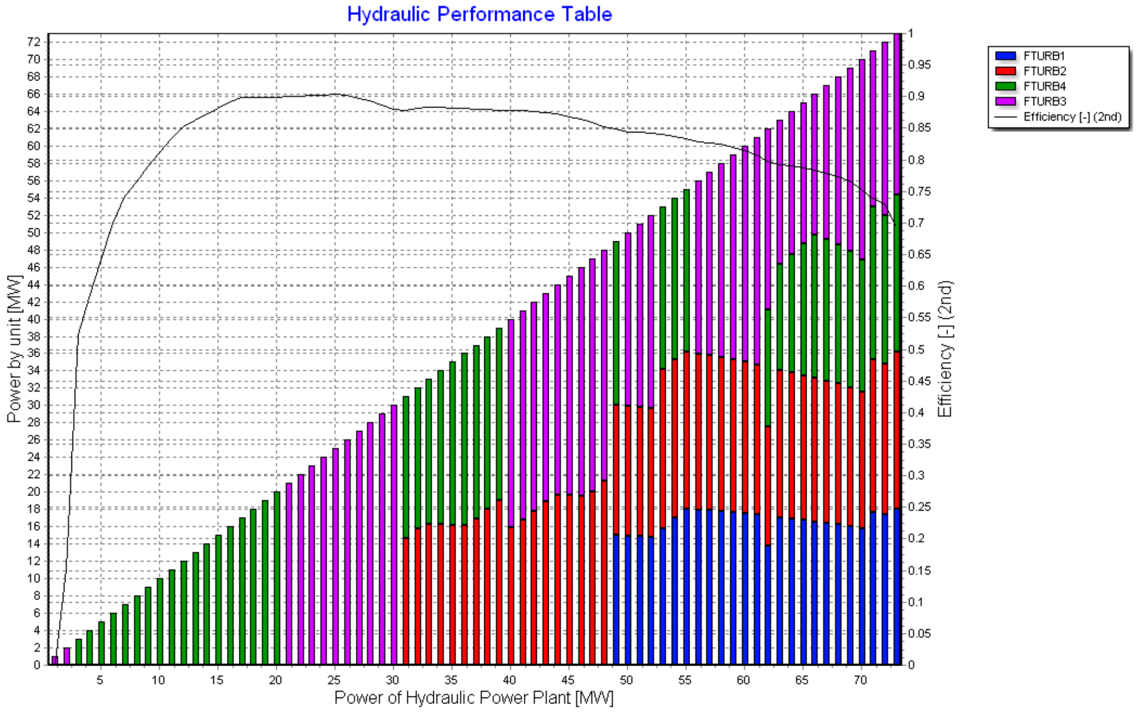


Figure 11 Hydraulic performance table for a given upstream water level and a hydraulic power plant with 4 Francis turbines, which provides the optimal distribution of power over the 4 units for a given total power set point and a given gross head.

2.5 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 option, a mathematical optimization 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, see Figure 12.

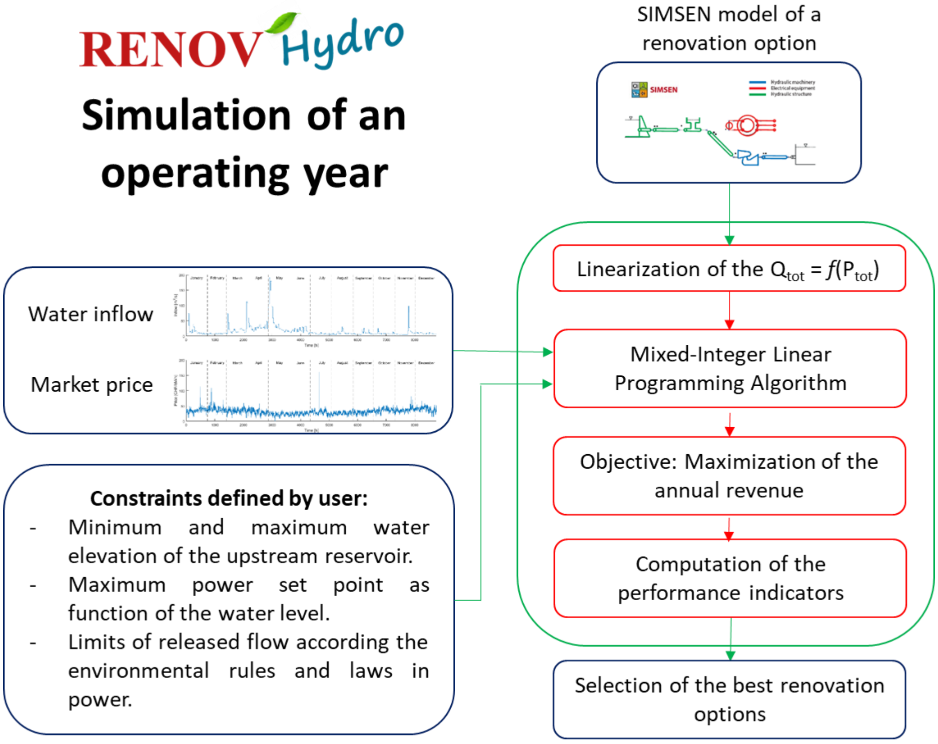


Figure 12 Detailed flowchart for the simulation of an operating year.

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 optimization problem can be written as:

- Objective function: $\max\left(C^{T}x\right)$ Maximize the revenue.
- Unknown variables: x Total power of the HPP 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 optimization problem. First, the reference year is divided into shorter periods of time: for instance, 12 months. The aim of the first stage optimization 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 return on investment for each renovation option. As the annual revenue has been maximized, the different technological renovation options can be analyzed 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.

2.6 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, see Figure 13. 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 [23].

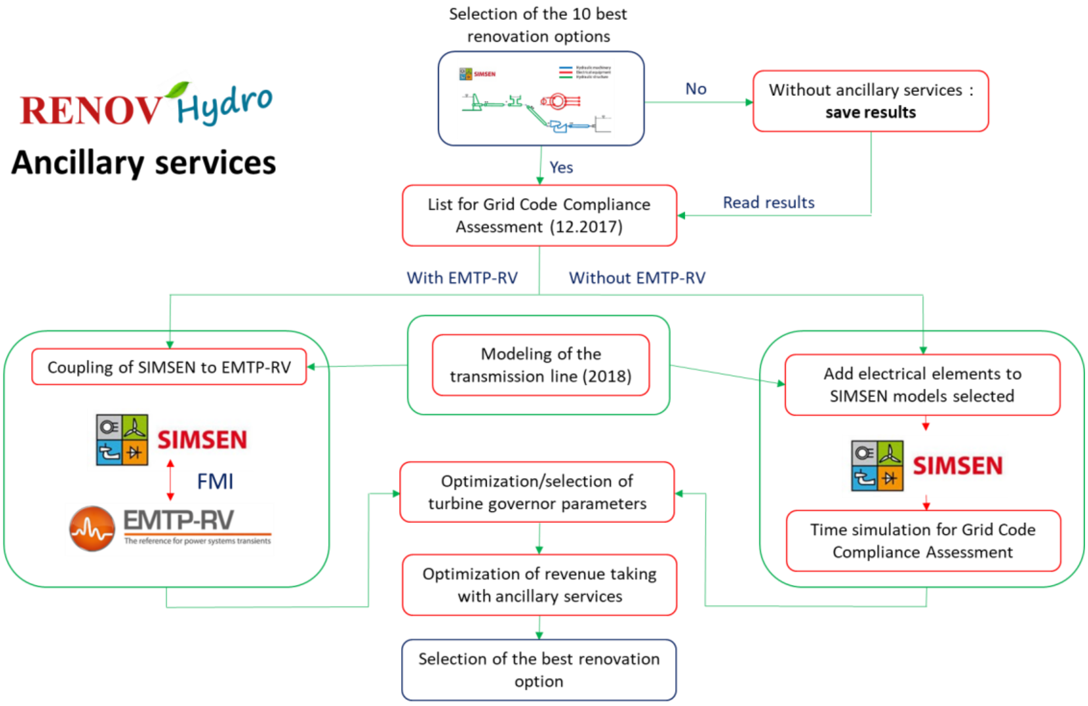


Figure 13 Detailed flowchart of the ancillary services analysis.

In order to automatically assess the primary control potential of the renovated hydroelectric power plant, it is necessary to have a simple and robust methodology to deduce the parameters of a PID controller. The control system used in the SIMSEN model is illustrated in Figure 14. The control system is a PID turbine governor with both speed and power control loops combined with the permanent droop. An Anti-Reset Windup is used to limit the integral contribution of the PID when a saturation is reached. Finally, the output signal of the PID controller is limited by a rate limiter to guarantee a system response that fulfils the opening/closing laws of the turbine and by a saturation to remain within physical limits of the distributor.

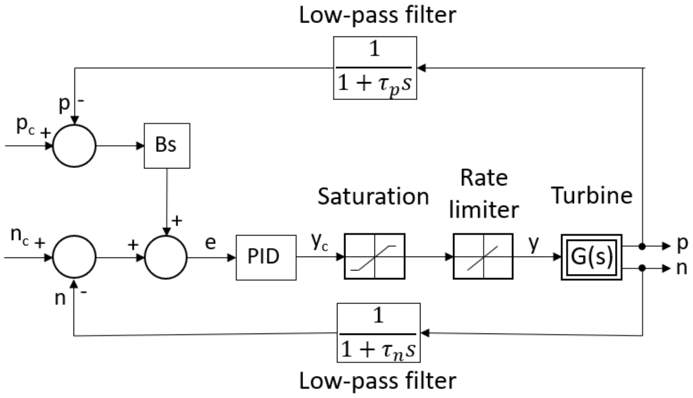


Figure 14 SIMSEN model of the control system.

- ***pc***: Dimensionless power set point.
- ***p***: Dimensionless mechanical power generated by the turbine.
- ***nc***: Dimensionless speed set point.
- ***n***: Dimensionless rotational speed of the turbine.
- ***Bs***: Permanent droop. $B_s = \frac{\Delta f}{f_n} / \frac{\Delta P}{P_n}$. *Bs* defines the contribution to primary reserve.

The block diagram of the PID series used is presented in Figure 15, where *K* is the proportional gain, *Ti* is the integral time constant, *Td* is the derivative time constant and *m* is the filter of the derivative term, range between 5 and 10.

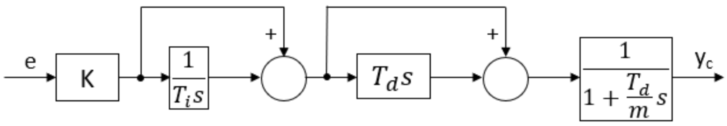
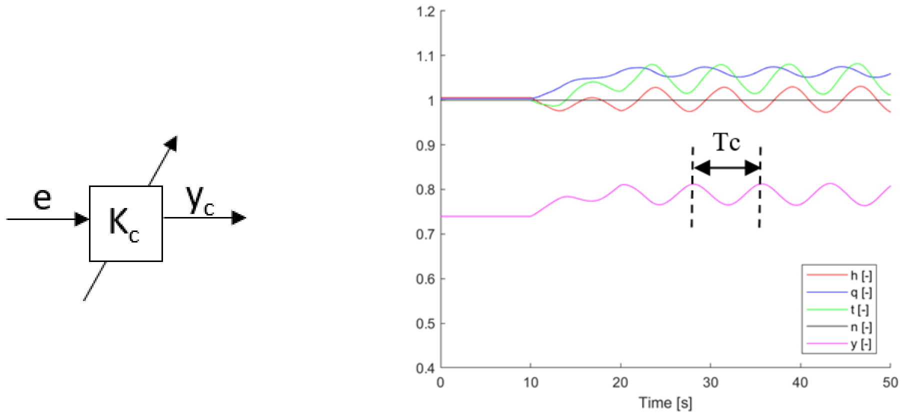


Figure 15 Block diagram of the PID controller in SIMSEN software.

The methodology used in the RENOVHydro library to determine the value of *K*, *Ti* and *Td* is based on the Ziegler-Nichols method [15]. This method is divided in two different steps:

- The integral time constant *Ti* and the derivative time constant *Td* are set to zero. The proportional gain *Kc* is then increased until it reaches the limit of stability, see Figure 16.



Block diagram of the proportional controller Transient behavior of the Francis turbine

Figure 16 First step of the Ziegler-Nichols method: Limit of stability.

According to the proportional gain obtained in the first step *Kc* and the oscillation period *Tc*, the *K*, *Ti*, and *Td* parameters of the PID controller in series are defined with the following rules:

- $K = 0.3 \cdot K_c$,
- $T_i = 0.5 \cdot T_c$,
- $T_d = 0.114 \cdot T_c$.

This methodology was applied to 40 different Francis turbines with specific speeds Nq ranging between 20 and 130 and the validation is described in Section 4.2.1.

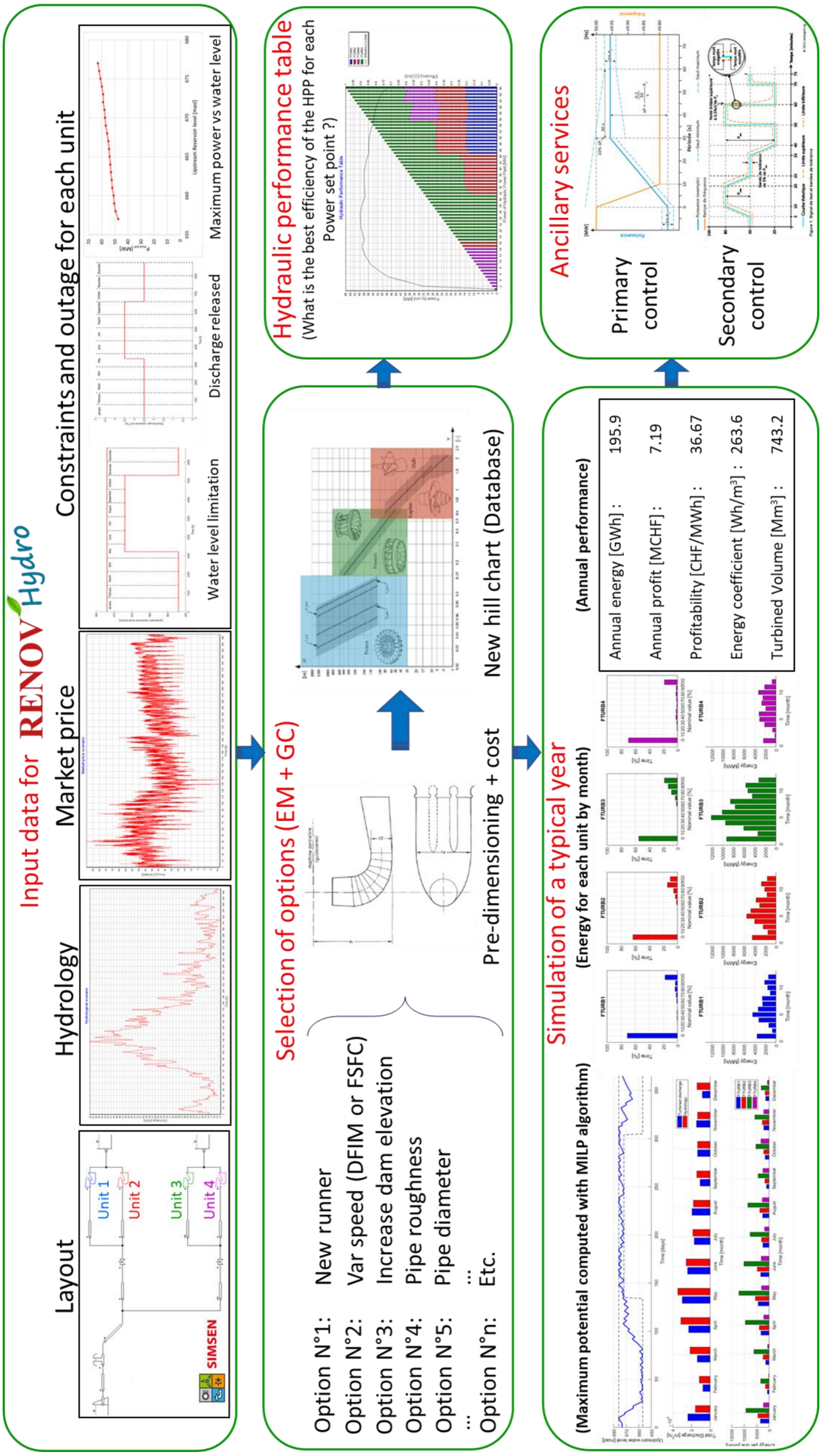


Figure 17 Workflow of the RENOVHydro project.

3 Description of the test cases

In the current context, with historically low electricity prices, significant climate change and the end of many hydraulic concessions in the coming years, it is important to enhance the value of the hydraulic energy by modernizing the swiss hydraulic power plants. In agreement with the two Swiss Power Utilities, 7 different hydraulic power plants (run-of-river and storage power plants) were selected and analyzed in details to determine the best renovation options. In this chapter, each test case is described and a selection of renovation options is proposed. The most interesting renovation options will be presented in details in Chapter 5.

3.1 Test case 1 (Run-of-river power plant)

The power house is equipped with 2 Francis turbines of 16 MW under a rated head of around 250 mWC and is illustrated in Figure 18. The reference diameter and the total inertia of the Francis turbine was estimated by RENOVHydro library. The water intakes are collected in the Rhône through a 3 km long gallery with a free surface and in an upstream reservoir through a 4 km long gallery. These flows are mixed into a surge tank characterized by a very small volume. With this small storage volume, this hydraulic power plant can be considered as a run-of-the-river power plant. Finally, the surge tank is connected to the power station through a 700 m long penstock.

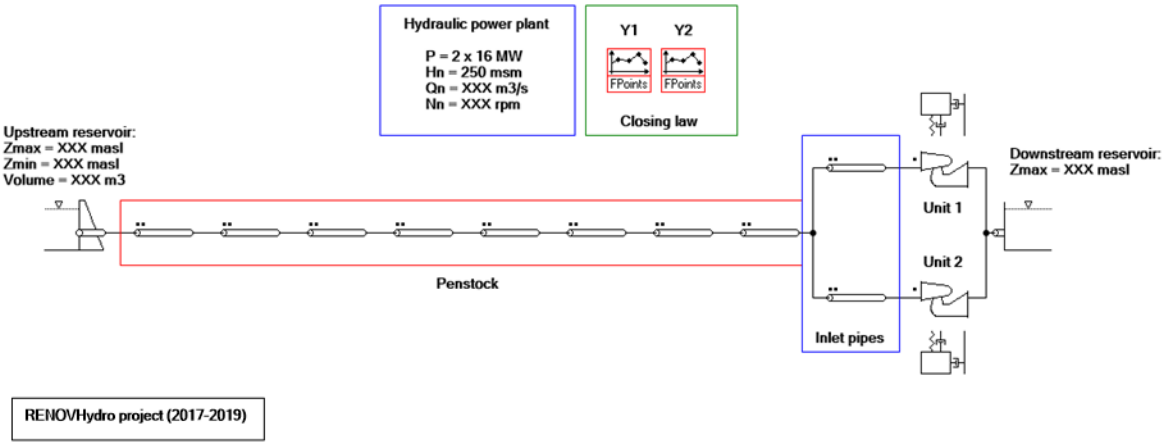


Figure 18 SIMSEN model of the test case 1.

During the project, various renovation options were investigated. Among these options, the most interesting are described in the following tables. In addition, the most relevant option is described in detail in Section 5.1.

Renovation option 1	
Description	With a dam height elevation of 1m, the storage volume would be increased by 13.3%.
Pros and cons	- The dwellings near the storage lake prevent the dam from being raised by more than 1 m. - Despite an increase in the storage volume, it remains very low and does not allow to store water for several days. → **For these reasons, this renovation option is not described in this document.**

Renovation option 2	
Description	Modifications of the units in the power house. Comparison between Pelton and Francis turbines.
Pros and cons	+ A detailed study has shown that turbines are mainly at rated power or at standstill. The type of turbine with the highest efficiency must then be selected! **→The Francis turbines must therefore be kept.**

Renovation option 3	
Description	The connection between upstream reservoir and the surge tank is currently an open channel. This connection can be replaced by a pressurized pipe. The water from the Rhône river is pumped in this penstock.
Pros and cons	+ The pressurized pipe could be installed in the current open channel. It is not necessary to dig a trench. The current connection between surge tank and the power plant could be kept. + The pressurized pipe increases the rated head of the turbine (+10 %). - The inflow from the Rhône river should be pumped inside the pressurized pipe. - Most of the water comes from the Rhône river and should therefore be pumped into the new pipe. **→ This renovation is expensive and is not described in this document.**

Renovation option 4	
Description	The connection between upstream reservoir and the surge tank is currently an open channel. A pressurized pipe could directly connect upstream reservoir to power station. The water from the Rhône river go through the current pipe between surge tank and the power station.
Pros and cons	+ A pressurized pipe could be installed in the current open channel. A new pipe should be installed between surge tank and power station. + The water from the Rhône river go through the current pipe between surge tank and the power station. + The water inflow from the Rhône river would be turbined by a specific Francis turbine. The water from upstream reservoir would be turbined by a second specific Francis turbine. - The maintenance of each Francis turbine would be more complicated. However, during the winter period, the turbines could be at a standstill because there is little water available. **→This renovation option will be described in detail in the section 5.1.**

3.2 Test case 2 (Run-of-river power plant)

The power house is equipped with 3 Francis turbines of 17 MW under a rated head of 250 mWC, see Figure 19. The reference diameter and the total inertia of the Francis turbine was estimated by RENOVHydro library. The water intakes are collected in the Rhône river and in a second river and mixed into a surge tank. The volume of this surge tank is very small and this hydraulic power plant can be considered as a run-of-the-river power plant. Finally, the surge tank is connected to the power station through a 700 m long penstock.

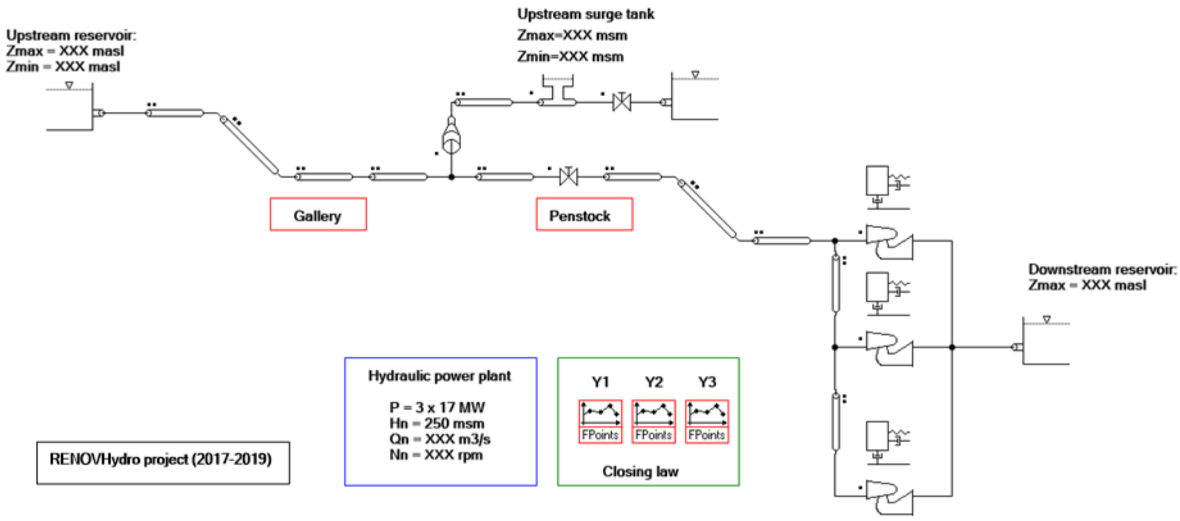


Figure 19 SIMSEN model of the test case 2.

During the project, various renovation options were investigated. Among these options, the most interesting is described in the following tables.

Renovation option 1	
Description	Modifications of the units in the power house. Comparison between 3 Pelton, 3 Francis or 2 Francis + 1 Pelton turbines.
Pros and cons	- A detailed study has shown that turbines are mainly at rated power or at standstill. The type of turbine with the highest efficiency must then be selected. → **The Francis turbines must therefore be kept.**

3.3 Test case 3 (Run-of-river power plant)

The power house is equipped with 2 Pelton turbines of 13 MW under a rated head of 730 mWC and is illustrated in Figure 20. The reference diameter and the total inertia of the Pelton turbine was estimated by RENOVHydro library. The water collected by an upstream small power station can be stored in an intermediate storage reservoir. Finally, this reservoir is connected to the main hydraulic power plant through a 2 km long penstock.

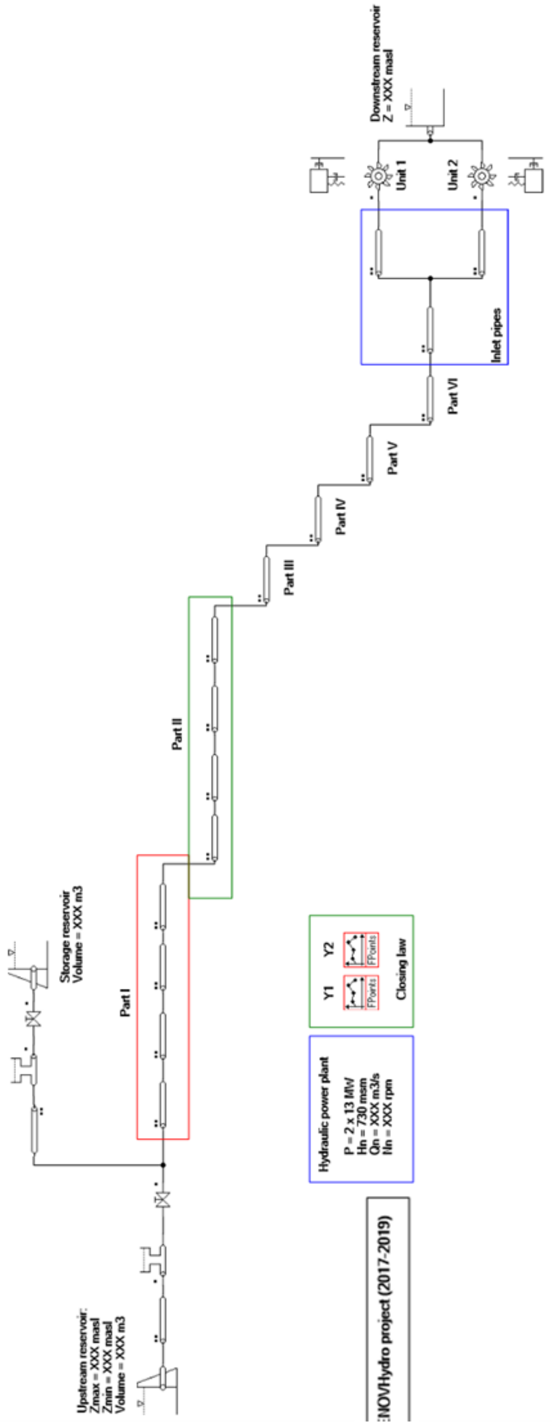


Figure 20 SIMSEN model of the test case 3.

3.4 Test case 4 (Run-of-river power plant)

The power house is equipped with 2 Pelton turbines of 13 MW and 30 MW under a rated head of 680 mWC and is illustrated in Figure 21. The reference diameter and the total inertia of the Pelton turbine was estimated by RENOVHydro library. The upstream reservoir is characterized by a large storage volume. The 3 km long penstock connects the upstream reservoir to the power house.

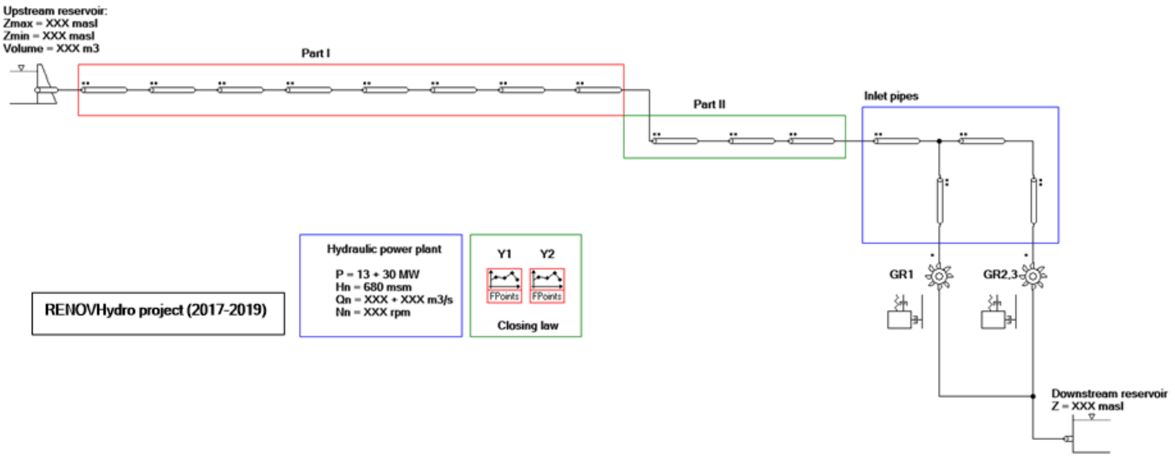


Figure 21 SIMSEN model of the test case 4.

During the project, various renovation options were investigated. Among these options, the most interesting are described in the following tables. In addition, the most relevant option is described in detail in Section 5.2.

Renovation option 1	
Description	With a dam height elevation of 9 m, the storage volume would be increased by 1000%.
Pros and cons	+ With a small modification of the dam, the storage capacity could be increased by a factor 10. - The expansion of the upstream reservoir may modify the biotope around the current mountain lake. + The original Pelton turbines features two different rated powers. The new units would be identical and thus facilitate the maintenance operations. → **This renovation option will be described in detail in section 5.2**.

3.5 Test case 5 (Run-of-river power plant)

The power house is equipped with 2 Pelton turbines of 32 MW under a rated head of 500 mWC and is illustrated in Figure 22. The reference diameter and the total inertia of the Pelton turbine was estimated by RENOVHydro library. The upstream reservoir is characterized by a medium storage volume. The 1.5 km long penstock connects the upstream reservoir to the power station.

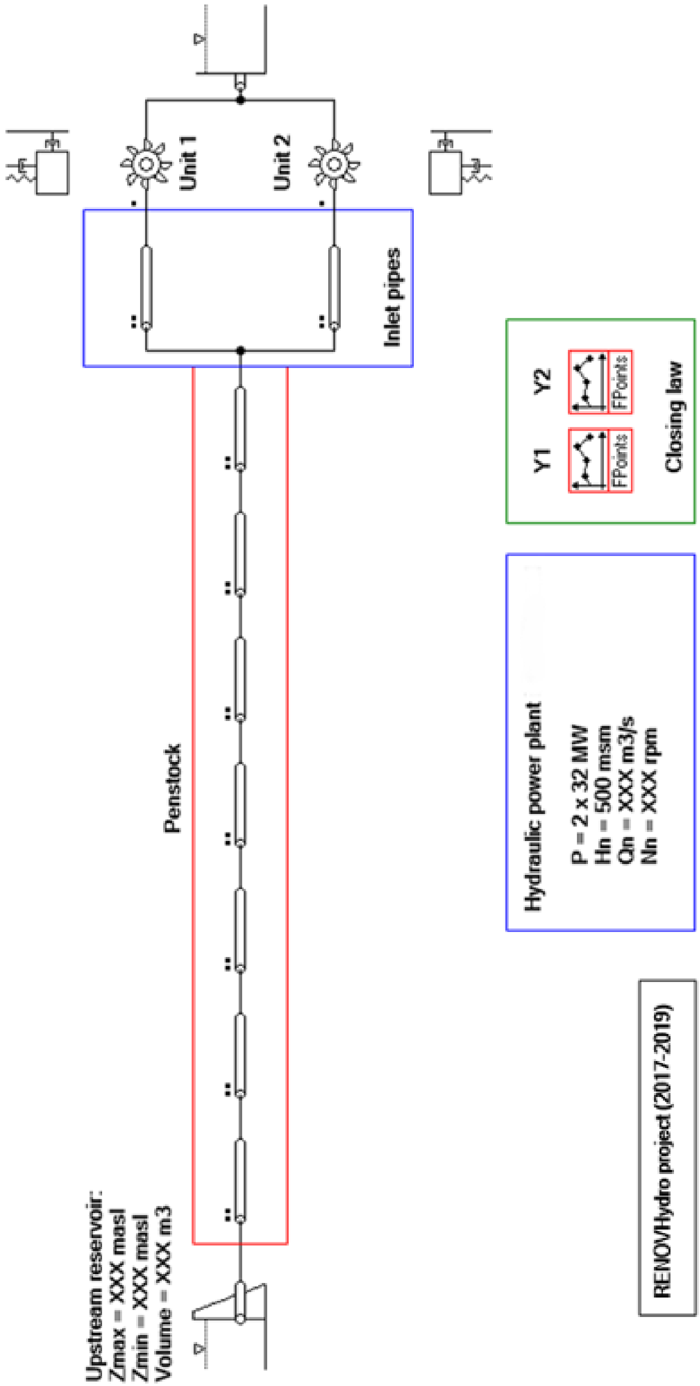


Figure 22 SIMSEN model of the test case 5.

3.6 Test case 6 (Storage power plant)

The power house is connected to the power station through a 6 km long gallery, a surge tank and finally a penstock with a length of 400 m. The power house is now equipped with 3 Francis turbines of 15.5 MW and 1 Francis turbines of 24.5 MW under a maximum head of 110 m [16].

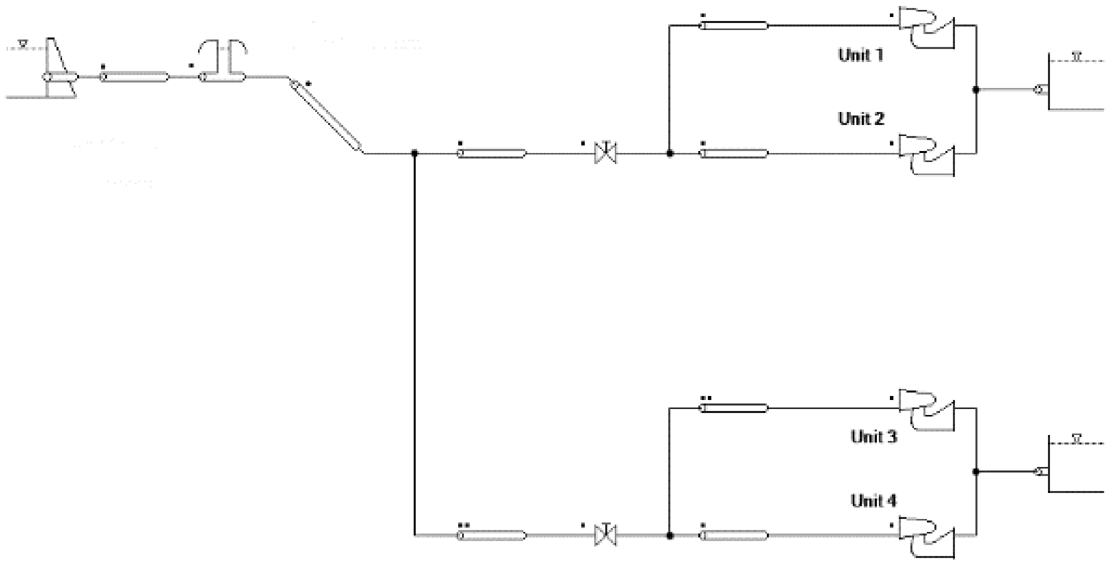


Figure 23 SIMSEN model of the test case 6

During the project, various renovation options were investigated. Among these options, the most interesting are described in the following tables. In addition, the most relevant option is described in detail in Section 5.3.

Renovation option 1	
Description	Modifications of the units in the power house. Comparison between 4 Francis, 3 Francis or 2 Francis turbines.
Pros and cons	+ The upgrade of the hydraulic turbines would increase the peak efficiency of each Francis turbine. - The pipe inlet would be modified if the number of units is reduced. **→ This renovation option will be described in detail in Section 5.3.**

3.7 Test case 7 (Storage power plant)

The power house equipped with 5 Francis turbines of 5 MW under a maximum head of 100 m. The turbines are connected to the upstream reservoir through a 1.6 km long gallery, a surge tank and finally a penstock with a length of 400 m.

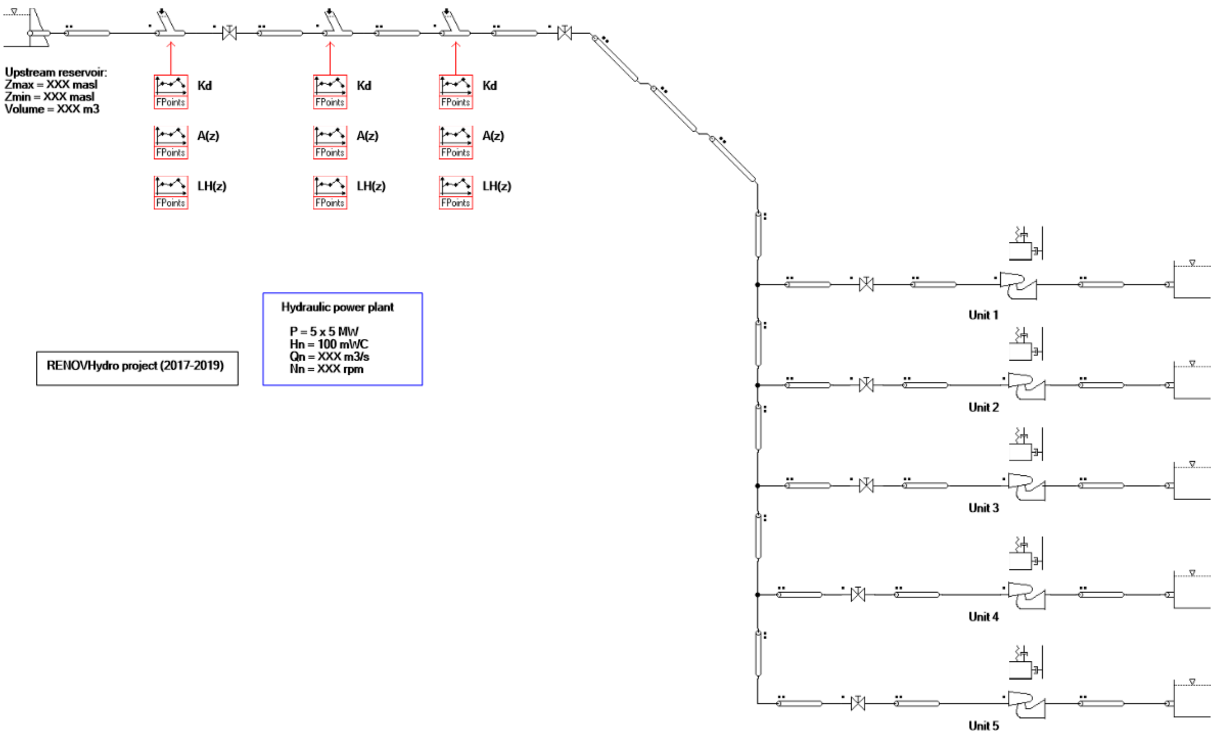


Figure 24 SIMSEN model of the test case 7

This test case is very interesting because the 5 units are very old and it becomes urgent to replace them quickly. Among the renovation options analyzed, the one described in the following table will be detailed in Chapter 5.4.

Renovation option 1	
Description	Modifications of the units in the power house. Comparison between 5 Francis, 3 Francis or 2 Francis turbines. For each case, 3 different energy losses are considered in the gallery (3mWC, 6mWC, 9mWC). Finally, for the best renovation option, a dam height elevation of 10 m and 20 m is investigated.
Pros and cons	+ The upgrade of the hydraulic turbines would increase the peak efficiency of each Francis turbine. + With a dam height elevation, the storage capacity could be increased and therefore the flexibility of the hydro power plant. - The modification of the number of units changes the architecture of the power house. → **This renovation option will be described in detail in Section 5.4**.

4 Validation of the methodology

The methodology of the RENOVHydro project was described in detail in Chapter 2. Some parts of this methodology are based on complex principles that require a special attention and validation. First, in the next section, the database of the performance hill charts for 3 different turbines is described. Then, the assessment of the frequency primary control capability is defined in Section 4.2. Finally, the co-simulation between EMTP and SIMSEN software is described in Section 4.3.

4.1 Validation of the characteristic curves

The energy and transient analysis of a hydro power plant is largely based on the performance hill chart of the hydraulic turbine. This non-linear information is essential to ensure the accuracy of the analysis of the different renovation options. Thus, as this information is rarely known by the user and more importantly for a new unit, an empirical model was developed to define hydraulic performance hill charts for hydraulic turbine according to its rated characteristics. In this section, the automatic creation of a performance hill chart for 3 types of hydraulic machines (Francis turbines, Pelton turbines and pump-turbines) is validated with a comparison of the transient behavior after an emergency shut down (ESD).

4.1.1 Francis turbine

The new database for Francis turbine contains more than 800 different characteristics, defined according to the value of the speed factor n_{ED} and the discharge factor Q_{ED} at the best efficiency point, see Figure 25 (blue points). By default, the peak efficiency of the hill chart in the database is fixed to 1. Then, during the selection of the turbine hill chart by the user of the RENOVHydro library, the peak efficiency is adapted according the value computed with the Gordon's equation [12], where the parameters depend on the diameter of the turbine, the year of commissioning and the specific speed of the runner. Finally, the parameters of this equation were updated to take into account the Francis turbine tested by the Laboratory of Hydraulic Machines (LMH).

This database was validated by comparing the transient behavior of 9 different turbines. The SIMSEN model of the real hydro power plant were used to simulate an emergency shut down after 10 seconds. The transient behavior of the Francis turbine was compared for two different performance hill charts: the real performance hill chart, experimentally measured on a reduced scale model, provides by the manufacturer and the associated hill chart from the new database (see Figure 25, green circles).

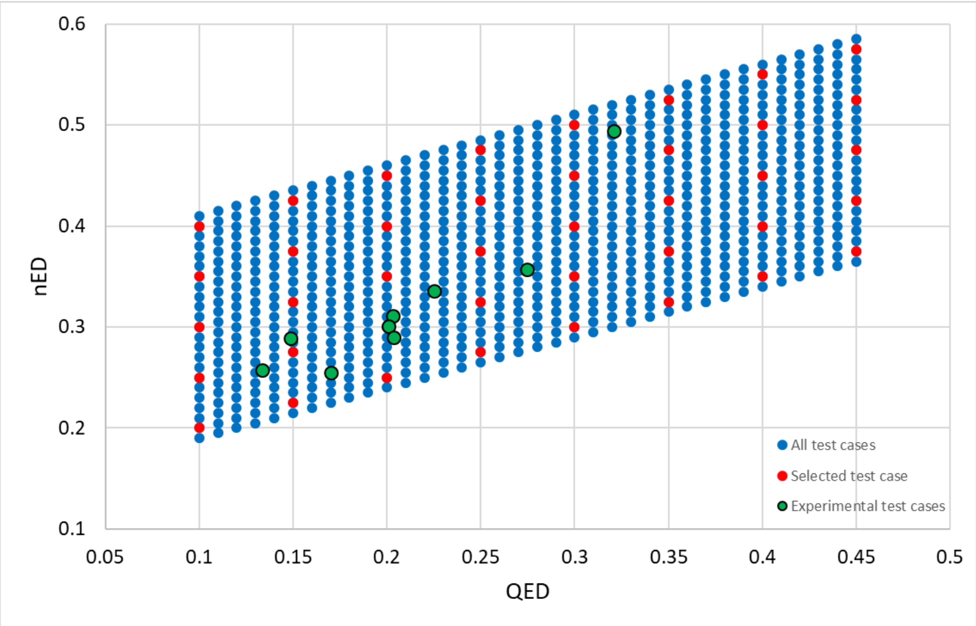


Figure 25 Range of performance hill char for a Francis turbine.
The blue circles represent the performance hill chart in the Francis database,
The red circles illustrate the 40 performance hill charts selected,
The green circles define the experimental performance hill chart.

An example of validation is illustrated in Figure 26 and Figure 27 for two different Francis turbines with a specific speed equal to 37 and 93, respectively [i]. There is a very good agreement between the two transient behaviors of the Francis turbine, validating the performance hill charts. A particular attention has been paid to small guide vane openings (GVO). Indeed, this part of the performance hill chart influences the overpressure and flow rate value during an ESD.

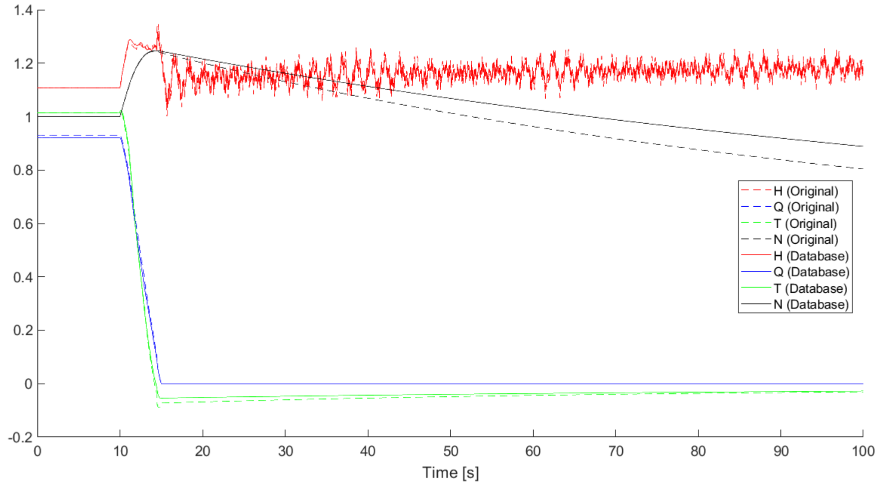


Figure 26 Comparison of an ESD transient behavior between the performance hill chart from database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 37).

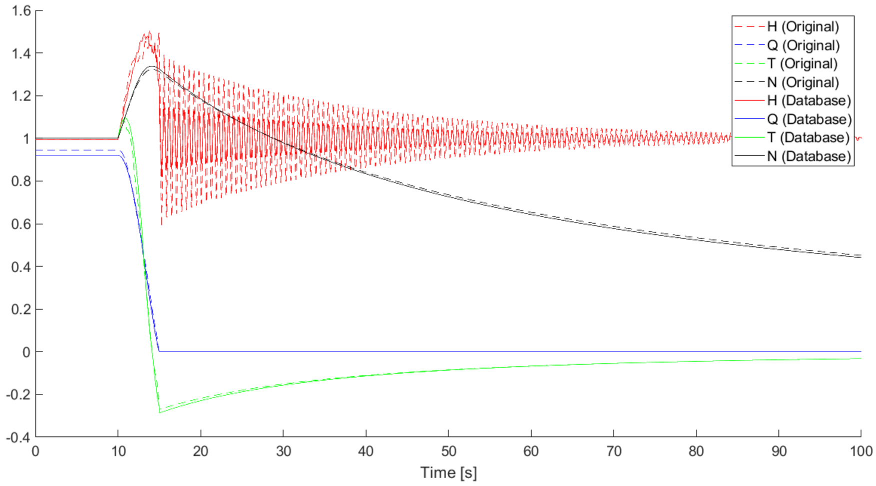
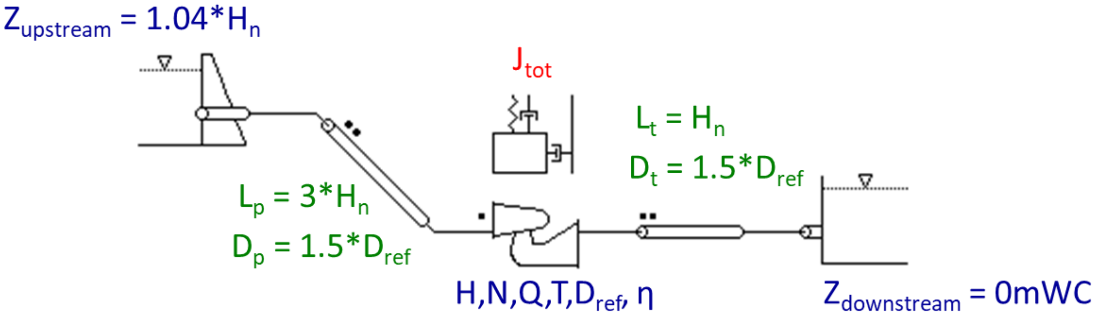


Figure 27 Comparison of an ESD transient behavior between the performance hill chart from database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 93).

Finally, to validate the dynamic behavior of the entire database range, 40 test cases were selected homogeneously (see Figure 25, red circles). For each test case, an automatic SIMSEN model was created according to the equations illustrated on Figure 28. With the speed factor n_{ED}, the discharge factor Q_{ED}, the mechanical power (fixed to P_m = 50MW) and the frequency of the grid (F_{grid} = 50Hz), the following parameters can be estimated with the RENOVHydro library:

- For Francis turbine
  - Rated head: Hn [mWC]
  - Rated rotational speed: Nn [rpm]
  - Rated discharge: Qn [m^3/s]
  - Rated torque: Tn [Nm]
  - Reference diameter: Dref [m]
  - Total inertia (generator+turbine): J_{tot} [kgm^2]
- Water level in the reservoir
  - Upstream reservoir: $Z_{upstream}$ = 1.04*Hn [masl]
  - Downstream reservoir: $Z_{downstream}$ = 0 [masl]
- Penstock
  - Length: Lp = 3*Hn [m]
  - Diameter: Dp = 1.5*Dref [m]
- Tailrace tunnel
  - Length: Lt = 3*Hn [m]
  - Diameter: Dt = 1.5*Dref [m]



$$\left.\begin{array}{l} n_{ED}+Q_{ED}\Rightarrow N_q \Rightarrow H \\ P_m = 50\text{ MW} \\ f_{grid}=50\text{ Hz}\end{array}\right\}\text{RENOVHydro}\Rightarrow \left(N,Q,D_{ref},\eta,J_{tot}\right)\Rightarrow \left\{\begin{array}{l}\tau_m=\dfrac{J_{tot}\omega^2}{P_m}\\ \tau_w=\dfrac{Q_n}{H_n}\sum\dfrac{L}{gA}\\ T_f=2\cdot\tau_m\end{array}\right.$$

Figure 28 SIMSEN model of a theoretical hydraulic power plant for each selected performance hill chart.

Each transient of the 40 Francis turbine test cases was analyzed to check the quality of each performance hill chart, see Figure 29.

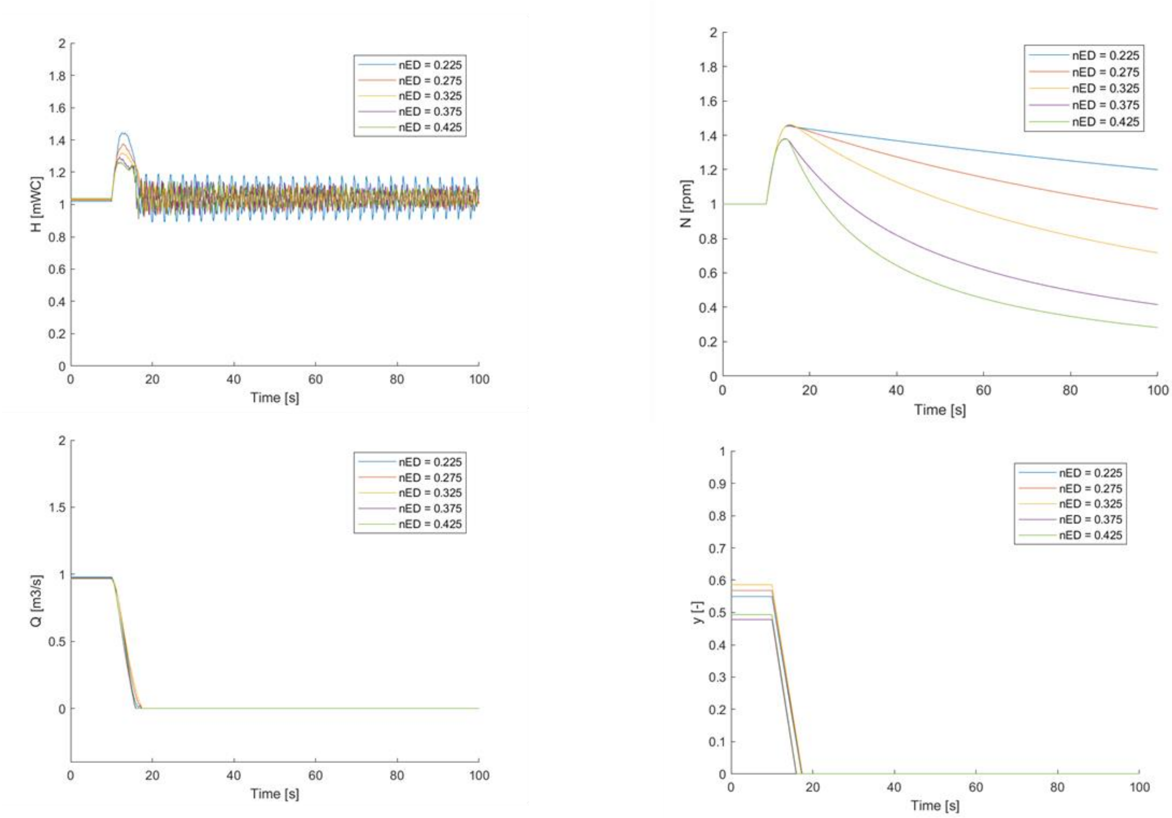


Figure 29 Transient behavior during an emergency shut down for 5 different n_{ED} and Q_{ED} = 0.15.

4.1.2 Pelton turbine

For the Pelton turbine, the performance hill chart is defined for only one injector. According to the value of the speed factor n_{ED}, the discharge factor Q_{ED} at the best efficiency point and the number of injectors, a performance hill chart is selected in the database. Moreover, for the Pelton turbine, the user can define a specific characteristic curve of the injector in a text file.

This database was validated by comparing the transient behavior of 4 different turbines. The SIMSEN model of the real hydro power plant were used to simulate an ESD after 10 seconds. The transient behavior of the Pelton turbine was compared for two different performance hill charts: the real performance hill chart, experimentally measured on a reduced scale model, provides by the manufacturer and the associated hill chart from the new database. An example of validation is illustrated in Figure 30 and Figure 31 for two different Pelton turbines with a specific speed equal to 12.7 and 19.2, respectively [j].

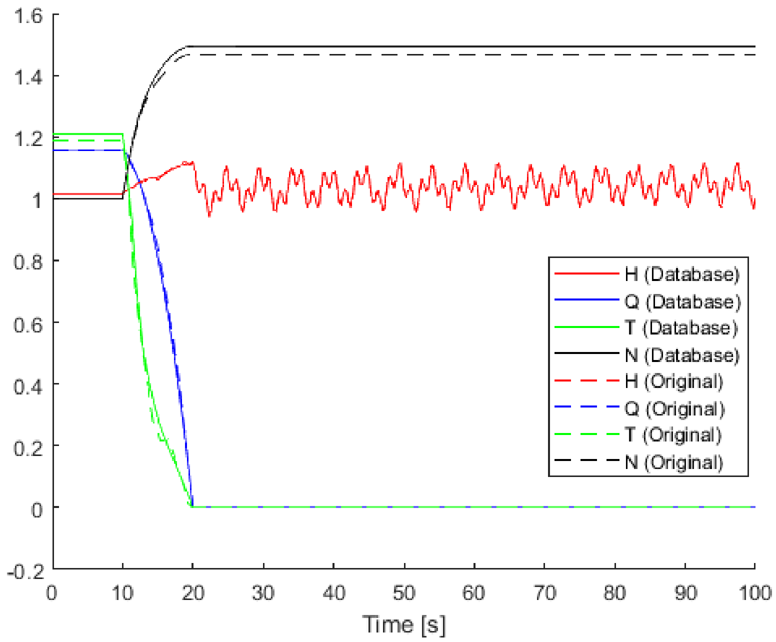


Figure 30 Comparison of an ESD transient behavior between the performance hill chart from the database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 12.7).

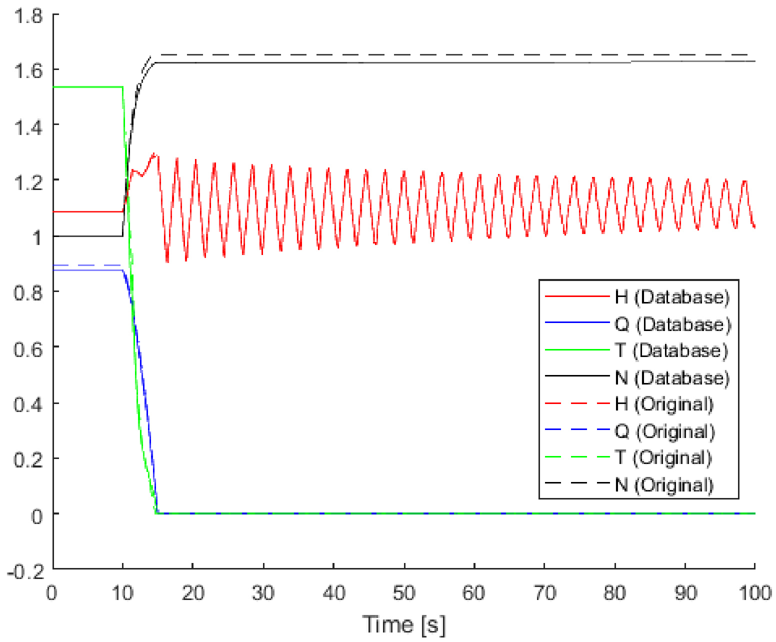
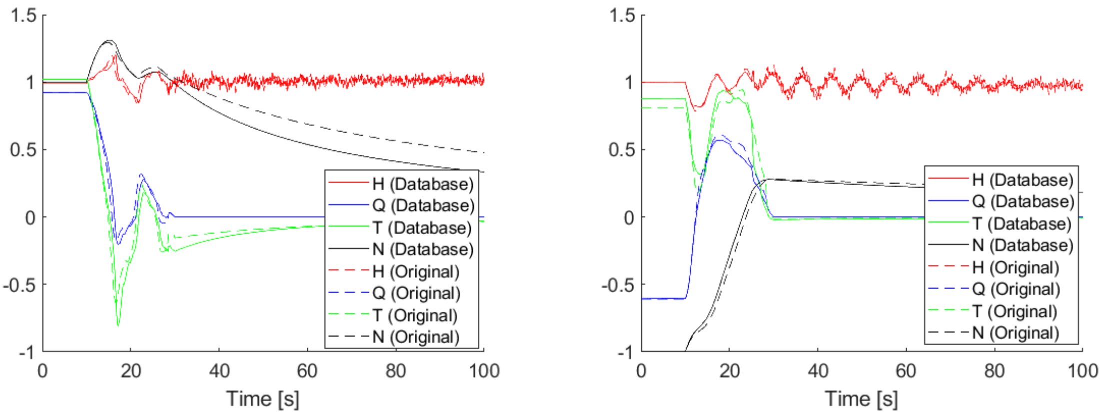


Figure 31 Comparison of an ESD transient behavior between the performance hill chart from the database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 19.2).

4.1.3 Pump-turbine

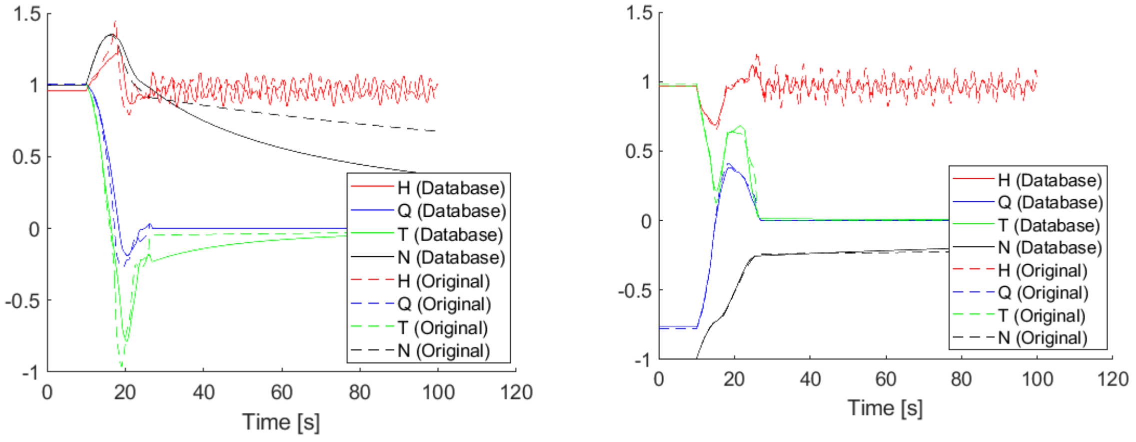
The new database for pump-turbine contains more than 900 different characteristics, defined according to the value of the specific speed, the speed factor n_{ED} and the discharge factor Q_{ED} at the best efficiency point in pumping mode. For this database, a special attention has been paid to the efficiency in turbine mode. The latter can be adjusted by the user if the targeted best efficiency of the pump-turbine would be slightly different.

This database was validated by comparing the transient behavior of 4 different turbines. The SIMSEN model of the real hydro power plant were used to simulate an ESD after 10 seconds. The transient behavior of the pump-turbine was compared for two different performance hill charts: the real performance hill chart, experimentally measured on a reduced scale model, provides by the manufacturer and the associated hill chart from the new database. An example of validation is illustrated in Figure 32, Figure 33 and Figure 34 for three different pump-turbines with a specific speed equal to 28, 38 and 54, respectively [k].



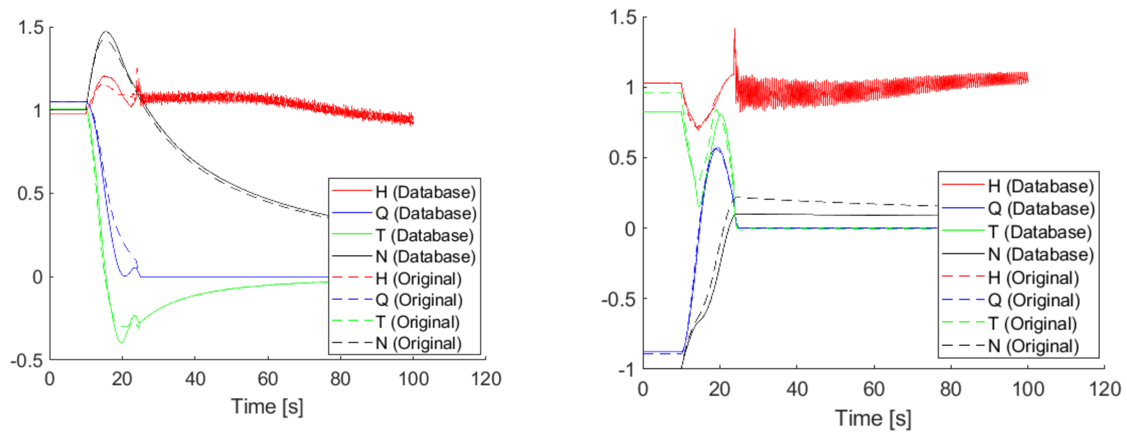
a) Turbine mode
b) Pumping mode

Figure 32 Comparison of an ESD transient behavior between the performance hill chart from the database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 28).



a) Turbine mode b) Pumping mode

Figure 33 Comparison of an ESD transient behavior between the performance hill chart from the database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 38).



a) Turbine mode b) Pumping mode

Figure 34 Comparison of an ESD transient behavior between the performance hill chart from the database (solid lines) and the performance hill chart from a manufacturer (dashed lines) (Nq = 54).

4.2 Assessment of the frequency primary control capability

4.2.1 Determination of the PID parameters of the control system

The assessment of the frequency primary control capability of a hydraulic power plant requires the determination of the PID parameters of the control system. The Ziegler-Nichols method described in section 2.6 is robust and can be applied regardless of the mechanical power of the hydraulic turbine.

In this section, the methodology was applied to the 40 Francis turbines with specific speeds Nq ranging between 20 and 130 and described in Section 4.1.1. For each test case, an automatic SIMSEN model was created according to the equations illustrated on Figure 28. According to the layout dimension, these PID parameters are guaranteed to the following ranges:

- Mechanical time constant: $T_m = \frac{J_{tot}\omega^2}{P} = [5.5 - 9.6]$
- Water starting time constant: $T_w = \frac{Q}{H}\sum\frac{L}{gA} = [0.9 - 2.6]$
- Hadley criteria [26]: $Hadley = \frac{T_m}{T_w} = [2.35 - 9.36]$
- Wave reflection time: $T_r = \frac{2L_{penstock}}{a_{penstock}} = [0.15 - 2.5]$

The test for primary control capability defined by the Swiss TSO, Swissgrid, is based on a frequency linear variation of 200 mHz in 10 seconds. The output power variation resulting from primary control response must be delivered within 30 seconds and remain between minimum and maximum threshold as depicted in Figure 35.

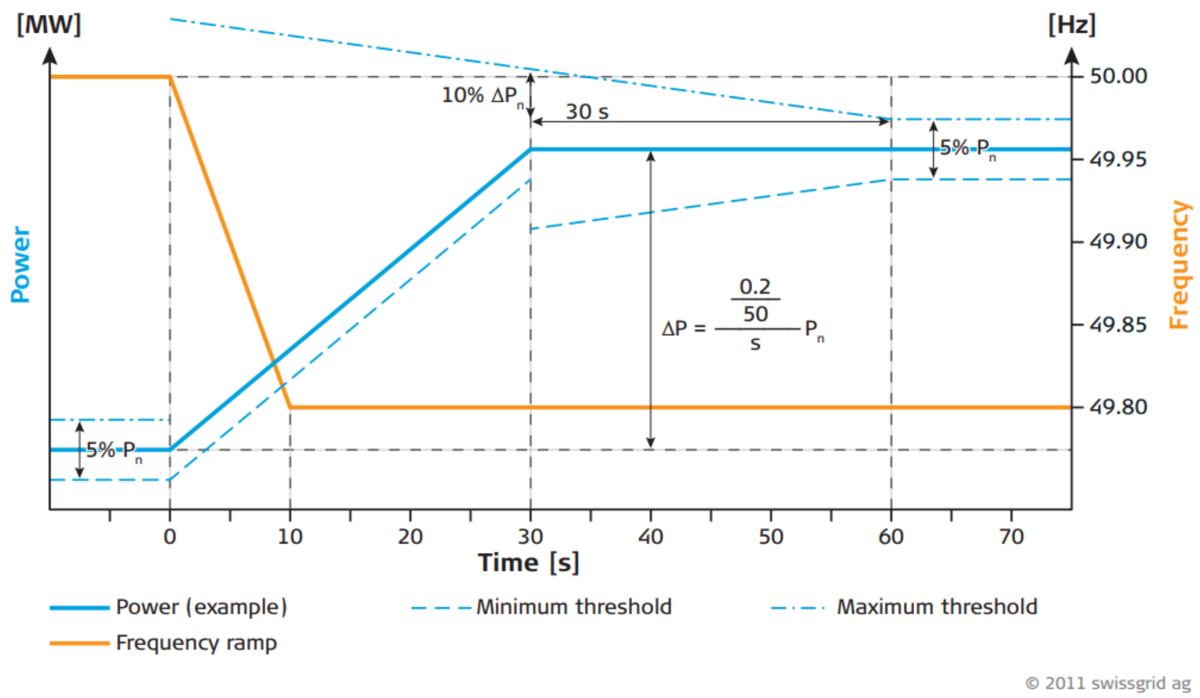


Figure 35 Test for primary control capability defined by Swissgrid [16]

For this study case, the permanent droop was fixed to 4%. Thus, a frequency variation of 200 mHz induces a power variation of 10%, i.e. 5 MW if the mechanical power is fixed to 50 MW. In order to compare the 40 different Francis turbines illustrated in Figure 25 (red circles), the system response for primary control capability are classified into 5 categories:

Swissgrid criteria validated (green point)	The output power response of the Francis turbine fulfilled the threshold defined by Swissgrid. The primary control is validated.
No respect of the minimum power (red point)	The output power response of the Francis turbine does not respect the minimum threshold imposed by Swissgrid.
Small oscillation of power (pink point)	Small oscillations of the output power response occur. This solution is not interesting for the grid stability.
Slow response of the PID controller (blue point)	The system response is too long and does not fulfil the minimum threshold defined by Swissgrid.
Unstable response of the PID controller (black point)	The output power response is unstable. The stability of the grid is compromised.

With the equations defined in Section 2.6, the system response fulfills the guarantees imposed by Swissgrid for each Francis turbine, see Figure 36. The response of the output power to a frequency variation of 200 mHz is illustrated in Figure 37 and Figure 38 for two different Francis turbines. With these new equations, the maximum primary ancillary service capabilities of the hydraulic power plant compatible with Transmission System Operator requirements can be easily assessed by gradually reducing the permanent droop.

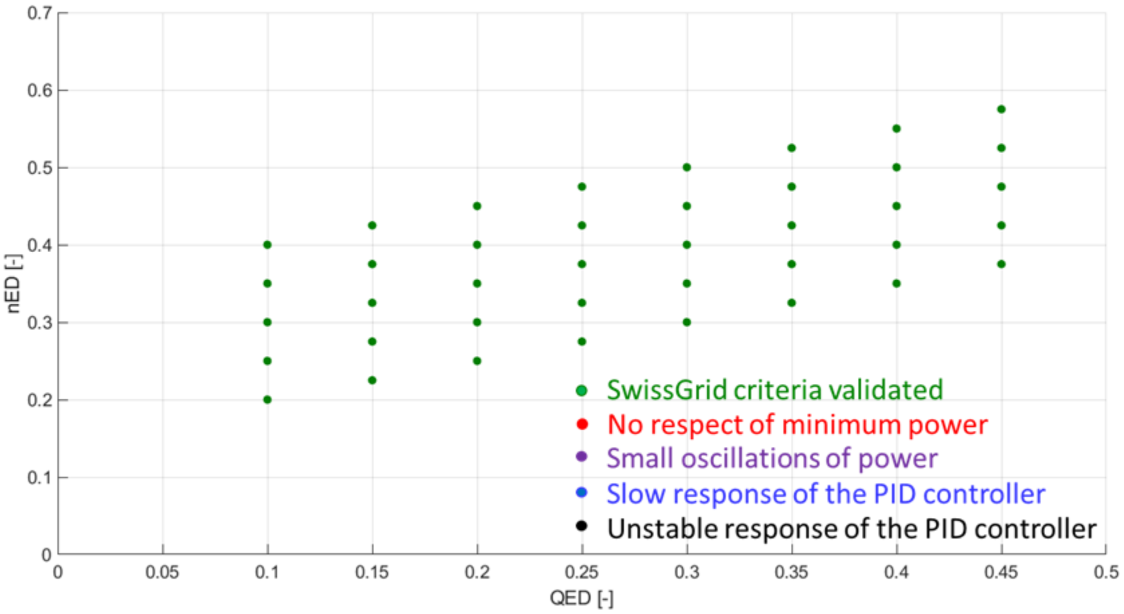
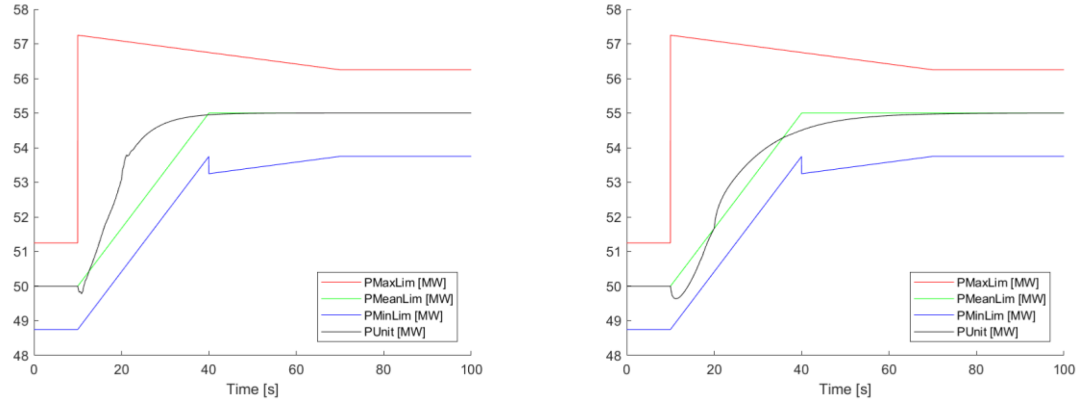
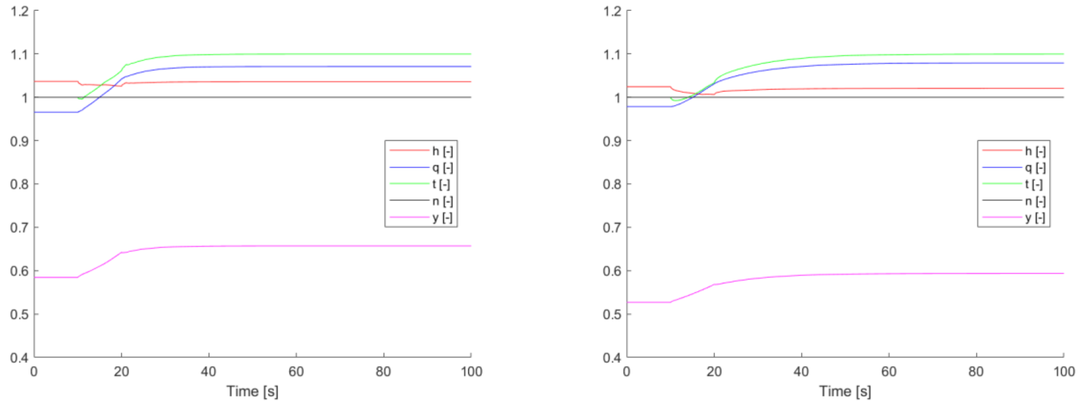


Figure 36 Summary of the response to a frequency variation of 200 mHz for the 40 different Francis turbines (P_m = 50 MW), using optimized parameters.



a) n_{ED} = 0.400, Q_{ED} = 0.100 (Nq = 42.07) b) n_{ED} = 0.375, Q_{ED} = 0.450 (Nq = 83.66)

Figure 37 Transient simulation of the response of the output power to a frequency variation of 200 mHz (P_m = 50 MW), using optimized parameters.



a) n_{ED} = 0.400, Q_{ED} = 0.100 (Nq = 42.07) b) n_{ED} = 0.375, Q_{ED} = 0.450 (Nq = 83.66)

Figure 38 Transient behavior of the Francis turbine after a frequency variation of 200 mHz (P_m = 50 MW), using optimized parameters.

4.2.2 Optimization of the ancillary services

For the hydro power plants that can provide primary and secondary capacity, the MILP energy dispatch model described in Section 2.5 was extended to include revenues and constraints associated with ancillary service provision. This new optimization assumes the power plant participates in weekly market with a symmetrical reserve provision. The optimization problem described in Section 2.5 can be rewritten as:

- Objective function: $\max\left(C^T x + D^W y + F^W z\right)$ Maximize the revenue.
- Unknown variables: x Total power of the HPP and water level in the reservoir.
  y Total power for primary reserve capacity.
  z Total power for secondary reserve capacity.
- Data on market price inputs: C^T price of the energy at time T.
  D^W price of the primary reserve for the week W.
  F^W price of the secondary reserve for the week W.

Similar to the original version of the MILP, the problem is formulated in two stages optimization problem to save computational resource and time. First, the reference year is divided into shorter periods of time: 52 weeks. The aim of the first stage optimization problem is to estimate weekly revenues from both energy and ancillary service markets and the water level at the end of the week. In the second stage, for each week, the hourly MILP problem is solved with respect to the water levels define in the first stage.

This new algorithm was applied to the test case N°6 with 4 Francis turbines and a large storage capacity. The price for the primary and secondary reserves in 2014 are described in the Figure 39. The maximum power reserve for both primary and secondary services was fixed to 15 MW. The optimal reserve capacity for primary and secondary control are illustrated in Figure 40. The optimal results for the water level variation in the upstream reservoir and the total power variation of the hydro power plant are described in Figure 41. Finally, the total revenue for this operating year is allocated as follows:

- Revenue from the energy market: 55.4 %
- Revenue from primary reserve: 10.2 %
- Revenue from secondary reserve: 34.4 %

The ancillary services provisions correspond to 44.4 % of the annual revenue and represents a very interesting financial part for the power utilities. Of course, these figures are only an example for the ancillary services. The user can define the number of units assigned to the primary and secondary control and the maximum power reserve.

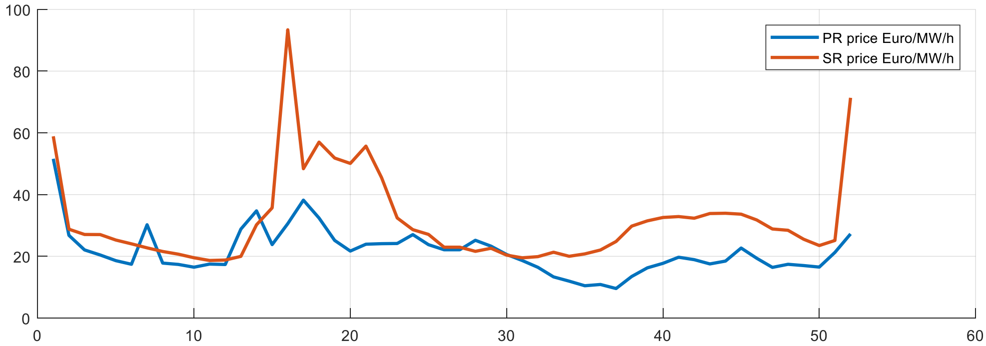


Figure 39 Price of the primary (PR) and secondary (SR) reserves from Swissgrid in 2014

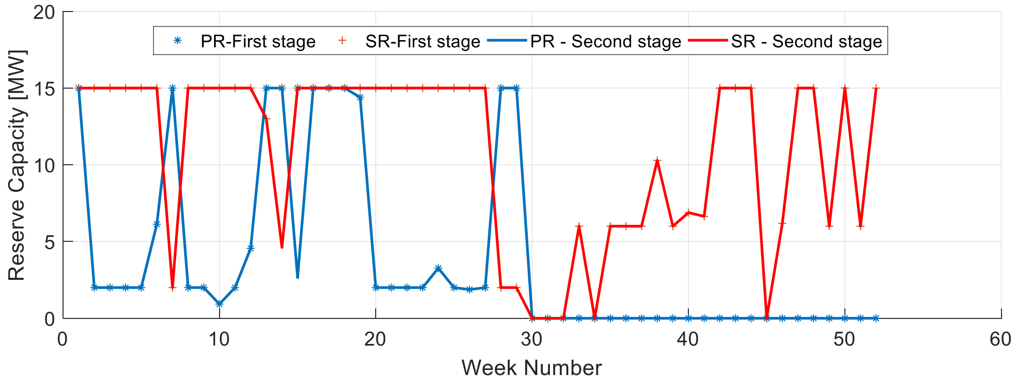


Figure 40 Reserve capacity for primary and secondary control in 2014

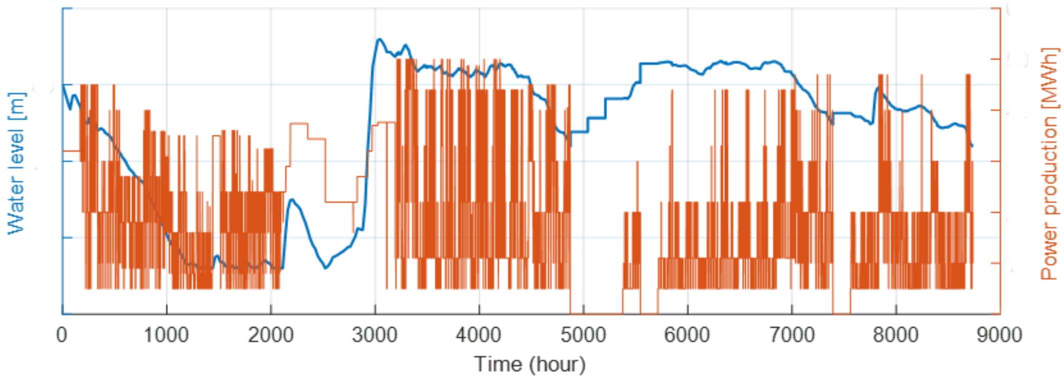


Figure 41 Variation of the water level (left axis) and the total power of the hydraulic power plant (right axis) as function of the hour.

4.3 Co-simulation between EMTP and SIMSEN software

4.3.1 Context

The coupling of several simulation software to perform time domain simulation using complementary models of each software is called co-simulation. Co-simulation is more and more used in R&D as well as in production. Many simulation softwares provide co-simulation capability. For the RENOVHydro project, the selected simulation tool that are selected to be complementary are SIMSEN and EMTP-RV. SIMSEN can handle complex detailed hydro-power units, featuring hydraulic and electromechanical equipment. EMTP-RV is often used to simulate electro-mechanical equipment along with the grid featuring in particular complex model of transmission lines. Power utilities might have a model of their electrical grid, or part of it, implemented in EMTP-RV. Hence, co-simulation between SIMSEN and EMTP-RV becomes relevant in particular for RENOVHydro.

Developing a co-simulation capability for a given simulation software is a complex task as it involves the development of a mathematical interface layer, on top of an informatics interface layer, as shown in Figure 42. The mathematical interface layer must specify how to exchange data and ensures that the mathematical description of the models, and its discretization, is uniquely defined. The informatics layer ensures that the data can be exchanged properly between several processes on a host machine. In particular, byte wise description of data format and remote procedure calls format are organized by this layer. Moreover, for a co-simulation capability to be useful, one needs to ensure that the other tools also implement, or are compatible with, the developed co-simulation protocol. In the RENOVHydro project existing co-simulation protocols where first assessed in order not to design one protocol from scratch. This is where the FMI (Functional Mockup Interface) standard came in.

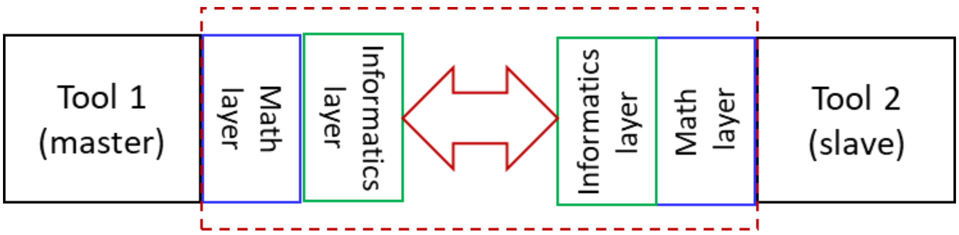


Figure 42 Layers of a co-simulation protocol.

4.3.2 FMI (Functional Mockup Interface)

The FMI standard defines in particular a co-simulation protocol. It is an open standard, meaning that the access to the specification documents and the SDK (Starter Development Kit) is free. Details about FMI can be found at fmi-standard.org. There are about thirty simulation tools that implement the FMI protocol either partly or fully. In particular, EMTP-RV integrates the FMI co-simulation features since 2017.

The FMI protocol defines the mathematic and the informatics layers of the co-simulation protocol. In FMI co-simulation, one of the simulation tools must take the role of “master” while the other tool takes the role of “slave”. The meaning of this master-slave relationship is that the master tool decides of the pace at which the time domain simulation is performed, i.e. the size of the integration time step and when the steps must be computed. In EMTP-RV both roles are implemented. During RENOVHydro project, the FMI standard was studied and it came out that it was eligible to be implemented in the SIMSEN software. It was decided that, for the RENOVHydro project, only the master role would be implemented for SIMSEN, which will allow performing SIMSEN-EMTP co-simulations with SIMSEN as master and EMTP as slave, as shown in Figure 43. Implementing the slave role for SIMSEN is left for future developments as it costs more than the master role.

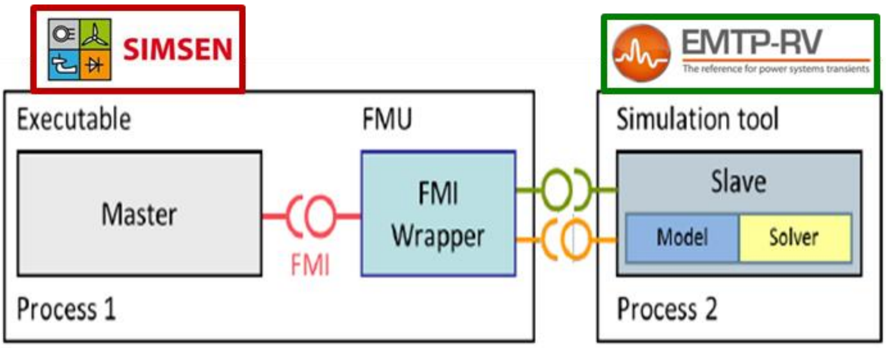


Figure 43 Co-simulation between SIMSEN and EMTP-RV using FMI protocol.

4.3.3 Implementation of FMI in SIMSEN

The implementation of the FMI co-simulation protocol in SIMSEN was split into two steps. The first step consisted in developing a FMI library in the development environment and language Delphi, which is the language in which the source code of SIMSEN is written. The development of this FMI library for Delphi, named *FMI4Delphi* hereafter, allowed to simply perform tests of co-simulation with the test cases provided by the FMI SDK and validate this *FMI4Delphi* library, independently of the SIMSEN context.
The second step of the implementation of the FMI co-simulation protocol in SIMSEN was to integrate the functions of the *FMI4Delphi* library into the source code of the SIMSEN software. In particular, the task was to insert at the right places the calls to the FMI functions within the main integration loop of the time domain simulation algorithm of SIMSEN.

4.3.4 Test cases

In order to test the implementation of the FMI co-simulation capability in SIMSEN, first the simple test cases provided by the FMI SDK were used. After successfully running simple co-simulations with these test cases, more complex test cases were built with the EMTP-RV software. Because EMTP-RV provides both the master and slave roles, we first performed EMTP-RV to EMTP-RV co-simulations to have reference results which could be used then to compare and validate the SIMSEN to EMTP-RV co-simulations. The test cases required particular attention because the full model is cut at the level of a line, i.e. both sides of the split model exchange currents and voltage, which are state variables of the model. In order to test the exchange of current and voltages between both tools, the developed test model consisted in an ideal voltage source and a passive resistive-inductive load. The ideal voltage source was put in the master tool (SIMSEN), while the load was put in the slave tool (EMTP-RV). Figure 44 shows a screenshot of this test model. This test case was simulated successfully in co-simulation SIMSEN to EMTP-RV as can be observed in Figure 45 and Figure 46 where the currents and voltages are compared between the reference co-simulation EMTP-RV to EMTP-RV and the tested SIMSEN to EMTP-RV co-simulation.

After this fundamental test case, a more advanced test case was developed, featuring generator and complex transmission line mode. The generator was placed in the SIMSEN model and the transmission line in EMTP-RV. This advanced test case was successfully run in a SIMSEN to EMTP-RV co-simulation.

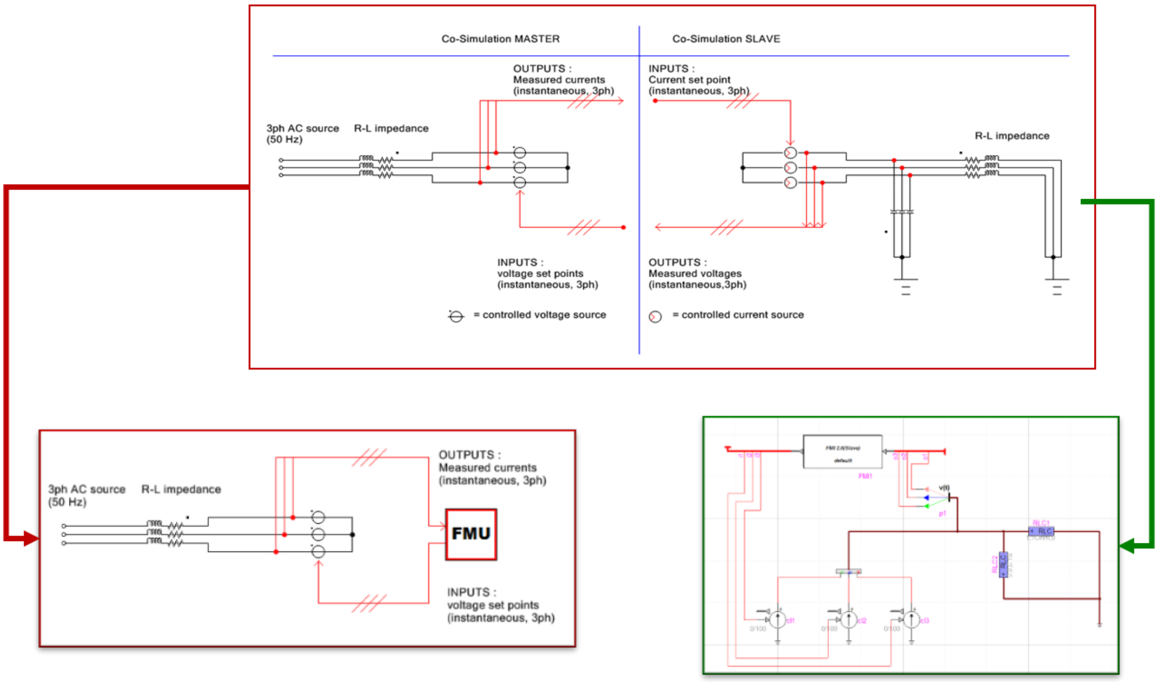


Figure 44 Test case used to validate co-simulations between SIMSEN and EMTP-RV featuring exchanges of state variables (currents).

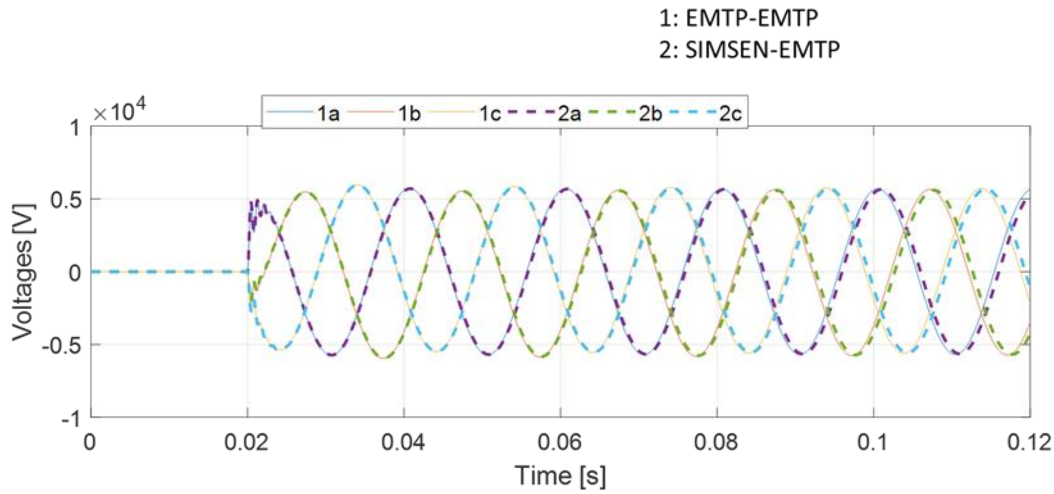


Figure 45.Comparison of the voltage at the point of connection.

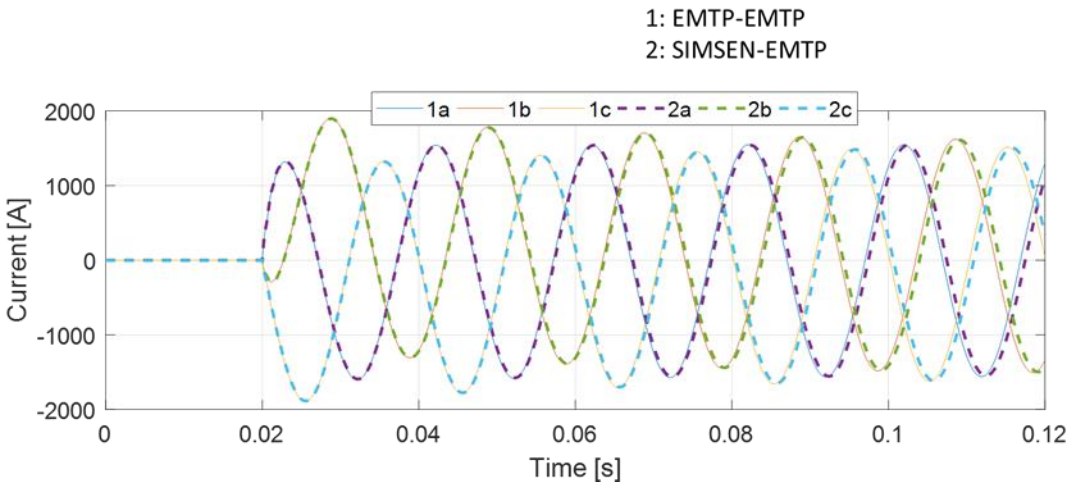


Figure 46 Comparison of the current at the point of connection.

4.3.5 Conclusion

During the RENOVHydro project, a co-simulation functionality was developed for SIMSEN, using the FMI co-simulation protocol. This feature allows performing co-simulation with any other simulation software that also implements the FMI co-simulation protocol. In particular, we could perform successfully co-simulations between SIMSEN and EMTP-RV, hence enabling the simulation of detailed hydro units in SIMSEN with a detailed transmission line and grid in EMTP-RV.

5 Test case modernization potential assessment

In this chapter, the RENOVHydro methodology is applied to 4 test cases (2 run-of-river power plants and 2 storage power plants) to validate the systematic assessment of renovation options. In particular, in Section 5.4, 27 different renovation options are considered. This case study is a perfect candidate to compare the computation time required to study all renovation options with and without RENOVHydro library. **It is important to note that most of the axes in this chapter will be dimensionless for reasons of confidentiality.**

5.1 Renovation option for the test case 1

The most interesting renovation option consists of assigning a Francis turbine to the water inflow from the Rhône river and a Francis turbine to the water inflow from the storage reservoir. The connection between storage reservoir and the surge tank is currently an open channel. A pressurized pipe could directly connect the storage reservoir to the power house. The water from the Rhône river would be turbined through the current pipe between the surge tank and the power house. With this renovation option, the maintenance of each Francis turbine would be more complicate, but during the winter period, the turbines could be at a standstill because there is little water available. Economically, this solution is very interesting with the current water inflows.

In this section, the current situation will first be analyzed with the RENOVHydro library to determine the annual revenue obtained with this hydraulic power plant and the cost of these electromechanical and civil options. Finally, the attractiveness of this solution will be quantified with the performance indicators.

5.1.1 Current situation

According the methodology used in the RENOVHydro library, the complete analysis of a hydraulic power plant requires the following information:

- A SIMSEN model of the hydraulic power plant was created. The power utility provided all the geometry of the waterway and the rated values of the Francis turbines. With these data, the complete numerical model was created. The total inertia, the reference diameter of the turbine and the performance hill chart of the Francis turbine were estimated by the new RENOVHydro library.
- The water inflow and the electricity price time history of the year 2017 were also provided by the power utility.
- No power limitation and no released discharge were defined for this test case.
- To validate this numerical model, the variation of the energy production in 2017 was compared with experimental measurement provided by the power utility, see Figure 47.

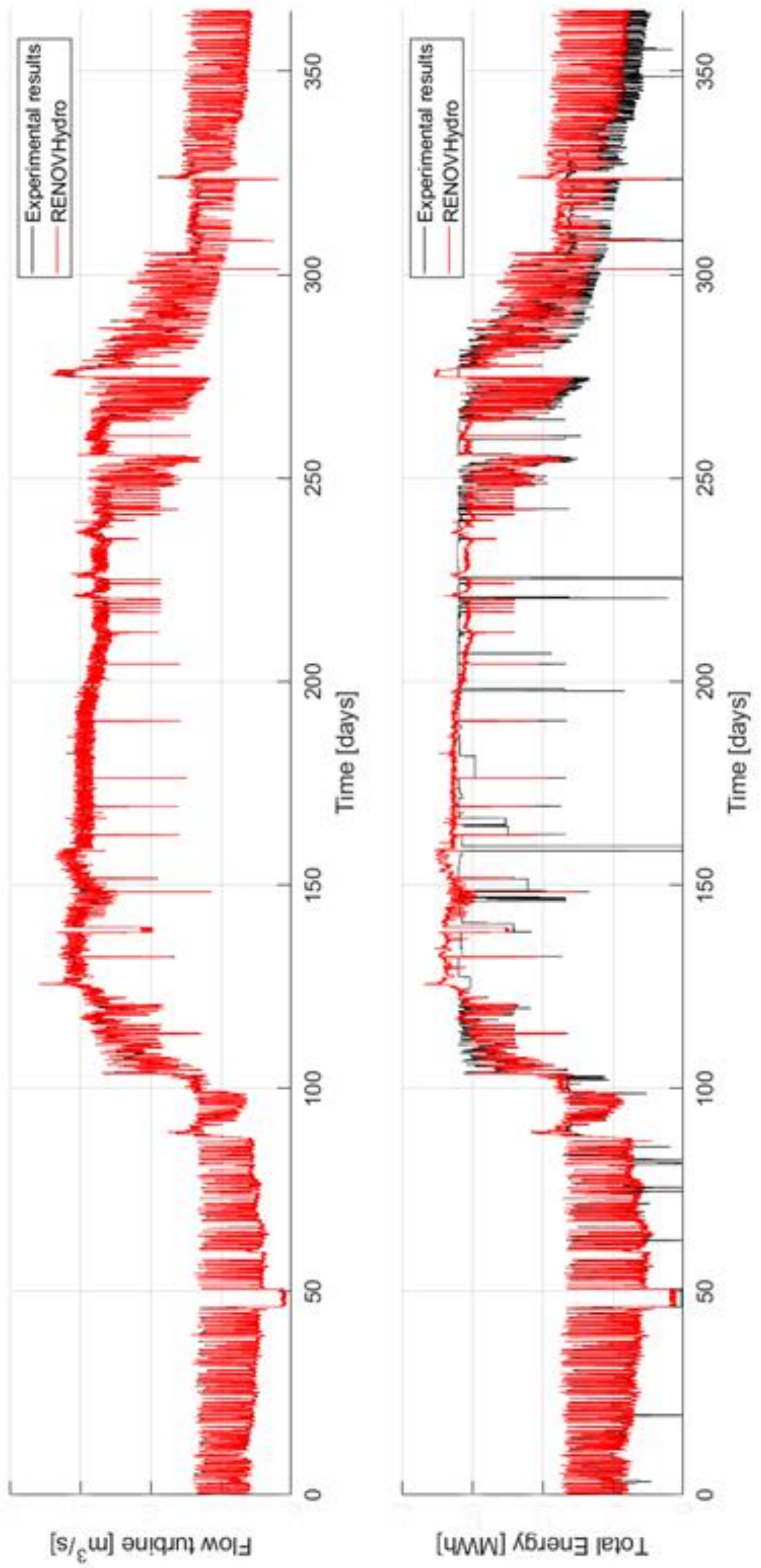


Figure 47 Turbined flow and energy production generated in 2017 (hourly time step). In black, the measurement provided by the power utility. In red, the numerical results with the RENOVhydro library.

5.1.2 Description of the renovation options

The renovation option consists of assigning a Francis turbine to the water inflow from the Rhône river and a Francis turbine to the water inflow from the storage reservoir. The waterway for the water inflow from the Rhône river does not need to be modified. The connection between storage reservoir and the surge tank is currently an open channel and would be replaced by a pressurized pipe.

- Length of the pipe: L = 3'890 m
- Diameter of the pipe: D = 1.8 m
- Steel cost: Cost ≈ 26 MCHF
- Installation cost: Cost ≈ 4.9 MCHF
- Considering the cost for the site installation, contingency costs, engineering fees and general expenses, the cost of the civil modification is in the range of 43 MCHF.

A new pressurized pipe should be installed between surge tank and the power house:

- Length of the pipe: L = 910 m
- Diameter of the pipe: D = 1.8 → 1.65 m
- Steel cost: Cost ≈ 5.9 MCHF
- Installation cost: Cost ≈ 1.1 MCHF
- Considering the cost for the site installation, contingency costs, engineering fees and general expenses, the cost of the civil modification is in the range of 9.8 MCHF.

With these civil modifications, the rated discharge and the rated head of each current hydraulic turbine would be modified and new Francis turbines should be installed. The cost of a unit estimated by RENOVHydro library takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications.

- The total cost of the 1st unit (27 MW) is in the range of 8 MCHF for water from the Rhône river.
- The total cost of the 2nd unit (22 MW) is in the range of 6.8 MCHF for water from the storage reservoir.

5.1.3 Conclusion of this test case

With this renovation option, the turbined volume is still the same, but the annual energy and the annual revenue would be significantly increased by 12.6% and 14.47%, respectively, see Figure 48. In this figure, the current values of the performance indicators are set as references and noted 'REF'. A more realistic view of the climate change will help to determine whether this option remains attractive for the next decades.

However, this study does not take into account all the technical details (legal framework, subsidy, concession renegotiation) related to the renovation of the hydraulic power plant, but only highlight the most interesting renovation options. **Thus, the performance indicators described are not absolute values, but only aids in decision-making.**

	Currently	Renovation Option
Annual energy [GWh]	REF	+12.6 %
Annual revenue [MCHF]	REF	+14.47 %
Energy coefficient [Wh/m3]	REF	+12.61 %
Turbined volume [Mm³]	REF	262.71

Figure 48 Comparison of the performance indicators between the current situation (Reference) and the renovation options.

5.2 Renovation option for the test case 4

The most interesting renovation option is to increase the storage volume of the upstream reservoir, see Figure 49, in order to better distribute water according to the price of electricity. The advantage of this solution is that thanks to the topology of the valley, an increase of the dam level of only 9 m would increase the storage volume by a factor of 10. With the current water inflow, this renovation option is barely profitable for the efficient use of the water.

In this section, the current situation will first be analyzed with the RENOVhydro library to determine the annual revenue obtained with this hydraulic power plant and the cost of these electromechanical and civil options. Finally, the attractiveness of this solution will be quantified with the performance indicators.

Figure 49 Current upstream reservoir.

5.2.1 Current situation

According the methodology used in the RENOVHydro library, the complete analysis of a hydraulic power plant requires the following information:

- A SIMSEN model of the hydraulic power plant was created. The power utility provided all the geometry of the waterway and the rated values of the Pelton turbines. With these data, the complete numerical model was created. The total inertia, the reference diameter of the turbine and the performance hill chart of the Pelton were estimated by the new RENOVHydro library.
- The water inflow and the electricity price time history of the year 2017 were also provided by the power utility.
- No power limitation and no released discharge were defined for this test case.
- The variation of volume of the upstream reservoir according the water elevation can be approximated with a trapezoid, see Figure 50.

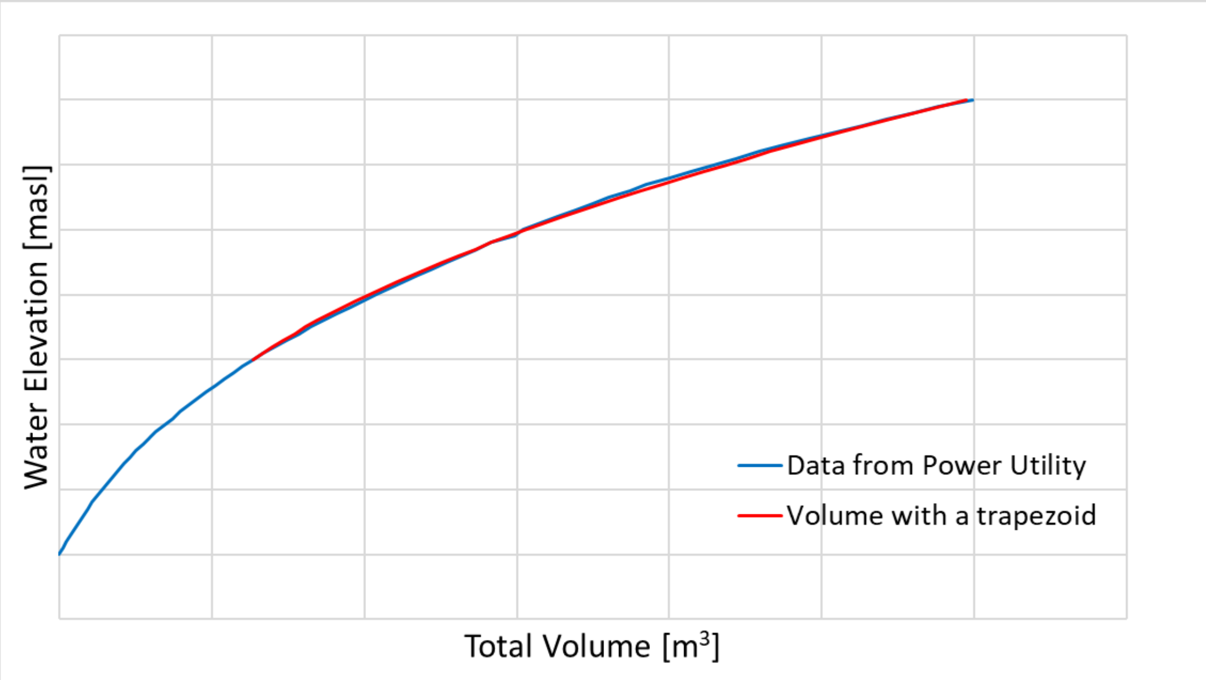


Figure 50 Current volume as function of the water elevation. The variation of the volume can be defined by a trapezoid.

To validate this numerical model, the variation of the energy production during the year 2017 was compared with experimental measurement provided by the power utility, see Figure 51. The monthly total energy illustrated in Figure 52 highlights that the majority of production occurred between May and August. As the storage reservoir is small, it is impossible to do seasonal storage and operate the turbine when the electricity price is attractive.

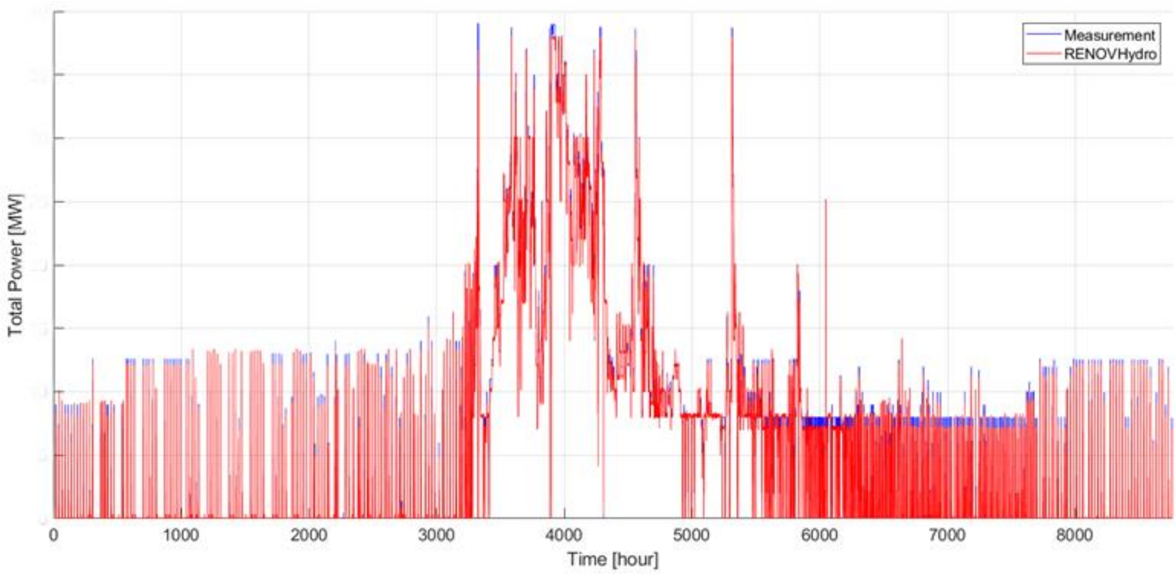


Figure 51 Energy production generated in 2017 (hourly time step). In blue, the measurement provided by the power utility. In red, the numerical results with the RENOVhydro library.

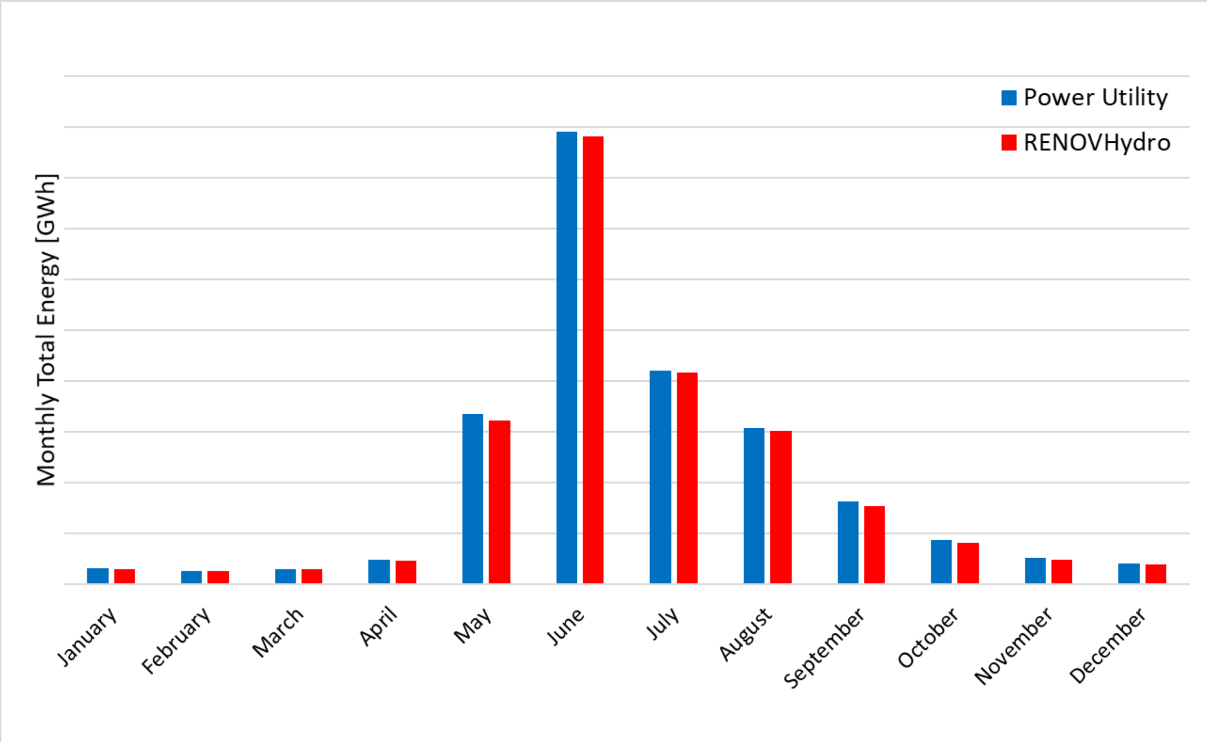


Figure 52 Comparison of the monthly total energy between the real data and numerical results with the RENOVHydro library.

5.2.2 Description of the renovation option

The renovation option consists in raising the dam height by 9 m for the reservoir expansion. The main modifications are the following:

- Increase of the maximum water level: +9m.
- Increase of the effective storage volume by a factor 10.
- Increase the rated head of each unit → New Pelton turbines.

One of the modules of the RENOVHydro library allows the sizing of renovation options for civil and electromechanics domains and the estimation of the costs generated. For this case, the following prices are estimated:

- With a length of crown of the dam fixed to 120 m, the new concrete volume is equal to 9'180 m^3. The concrete price is fixed to 500 CHF/m^3. Considering the cost for the site installation, contingency costs, engineering fees and general expenses, the cost of the civil modification is in the range of **6.4 MCHF**.
- The cost of the unit takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications. The total cost is in the range of **6.0 MCHF**.

5.2.3 Conclusion of this test case

With this increase of the upstream storage volume, the turbined volume and the water inflow are still the same. However, the turbined volume can now be delayed due to the storage and the units can be operated at higher efficiencies and at times when the price of electricity is more attractive, see Figure 53. The current potential energy stored in the upstream reservoir is therefore better valued and the annual revenue can be increased by 5.36%, see Figure 54. In this figure, the current values of the performance indicators are set as references and noted 'REF'. Finally, this renovation option offers a small increase in annual revenue despite a very large increase of storage reservoir. Indeed, the water inflow are still limited and a pumped-storage solution should be interesting to enhance the value of this new large storage capacity. A more realistic view of the climate change will help to determine whether this option remains attractive for the next decades.

These initial conclusions are not final because not all economic and legal aspects, such as subsidies, government assistance, concession renegotiation have been taken into account.

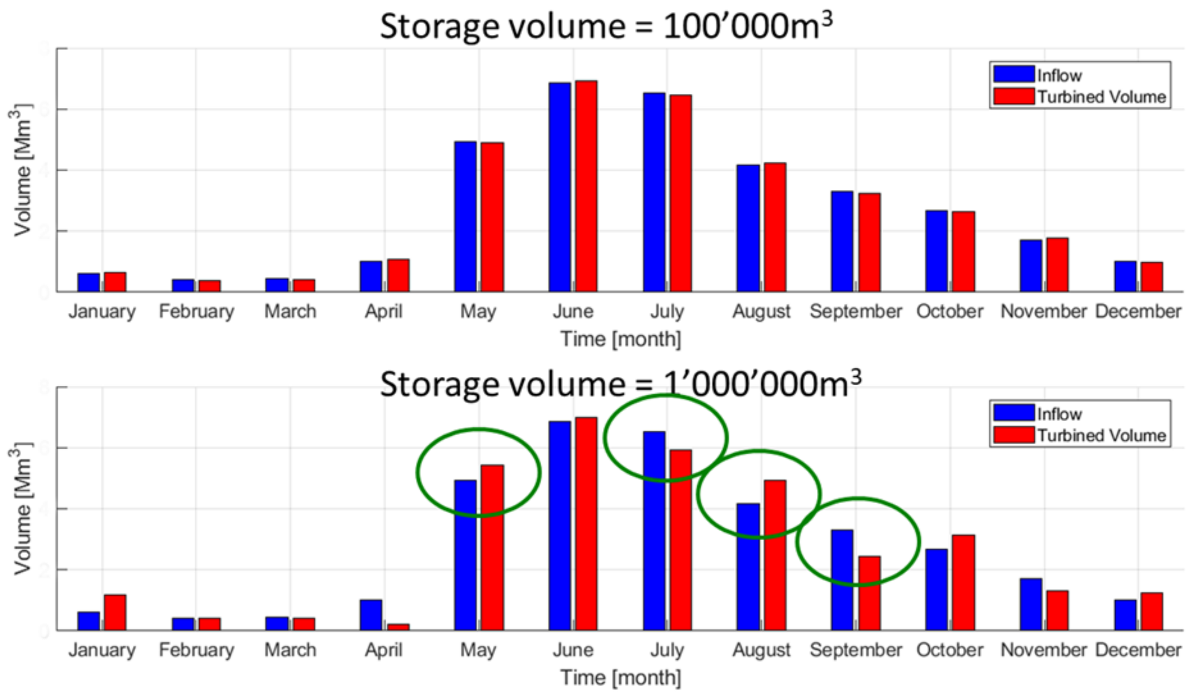


Figure 53 Comparison of the turbined volume and the inflow for the two different reservoirs. With the big reservoir, the turbined volume is no longer always equal to the volume of water inflow.

	Currently	New storage
Annual energy [GWh]	REF	+0.25 %
Annual revenue [MCHF]	REF	+5.36 %
Average unit revenue [CHF/MWh]	REF	+ 5.02 %
Turbined volume [Mm³]	REF	33.64

Figure 54 Comparison of the performance indicators between the current situation (Reference) and the renovation options.

5.3 Renovation option for the test case 6

In previous years, two units were replaced by a new unit with a higher mechanical power. It is interesting to investigate whether this renovation option can also be applied to the other 3 remaining units. With the systematic approach proposed by RENOVHydro library, it is possible to compare a layout with 2 units, 3 units and 4 units and thus determine which configuration would provide the higher annual revenue.

To answer this question, the current situation will first be analyzed with the RENOVhydro library to determine the annual revenue obtained with this hydraulic power plant and the cost of these electromechanical and civil options. Finally, the attractiveness of this solution will be quantified with the performance indicators.

5.3.1 Current situation

According the methodology used in the RENOVHydro library, the complete analysis of a hydraulic power plant requires the following information:

- A SIMSEN model of the hydraulic power plant was created. The power utility provided all the geometry of the waterway and the rated values of the Francis turbines. With these data, the complete numerical model was created. The total inertia, the reference diameter of the turbine and the performance hill chart were estimated by the new RENOVHydro library.
- The water inflow and the electricity price time history of the year 2017 were also provided by the power utility.
- A minimum and maximum water level are defined for the upstream reservoir and illustrated in Figure 55.
- A released flow in normal operating conditions is applied, see Figure 56.
- A maximum power set point for the hydro power plant as function of the water level is defined for the upstream reservoir.
- The variation of volume of the upstream reservoir according the water elevation can be approximated with a trapezoid.

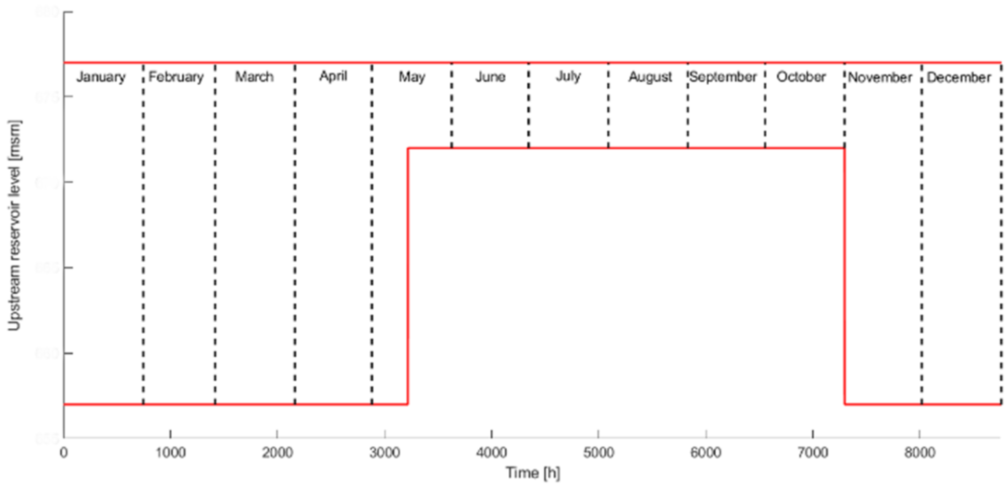


Figure 55 Minimum and maximum water levels in the upstream reservoir throughout the year.

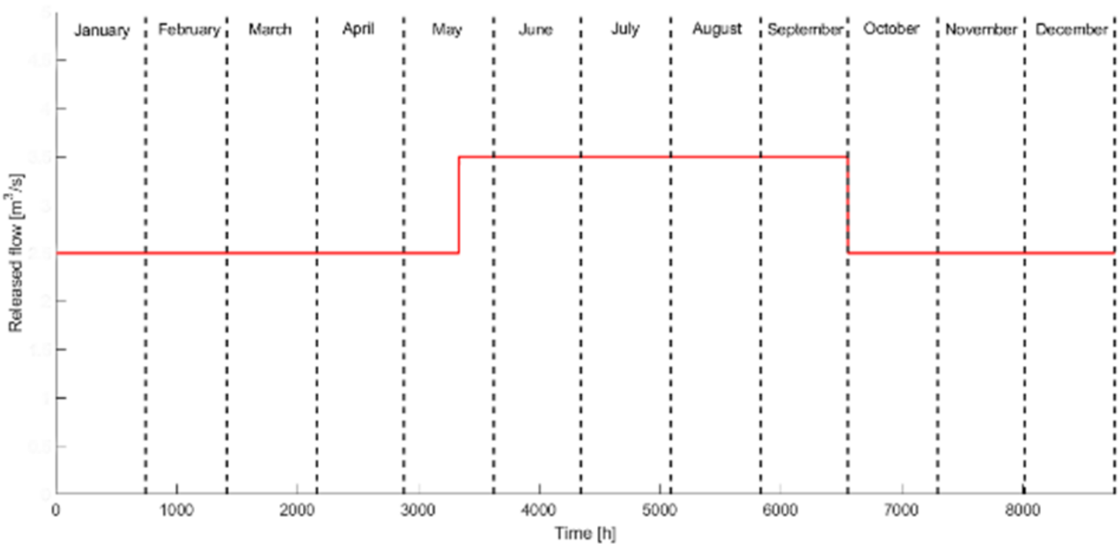


Figure 56 Released flow throughout the year.

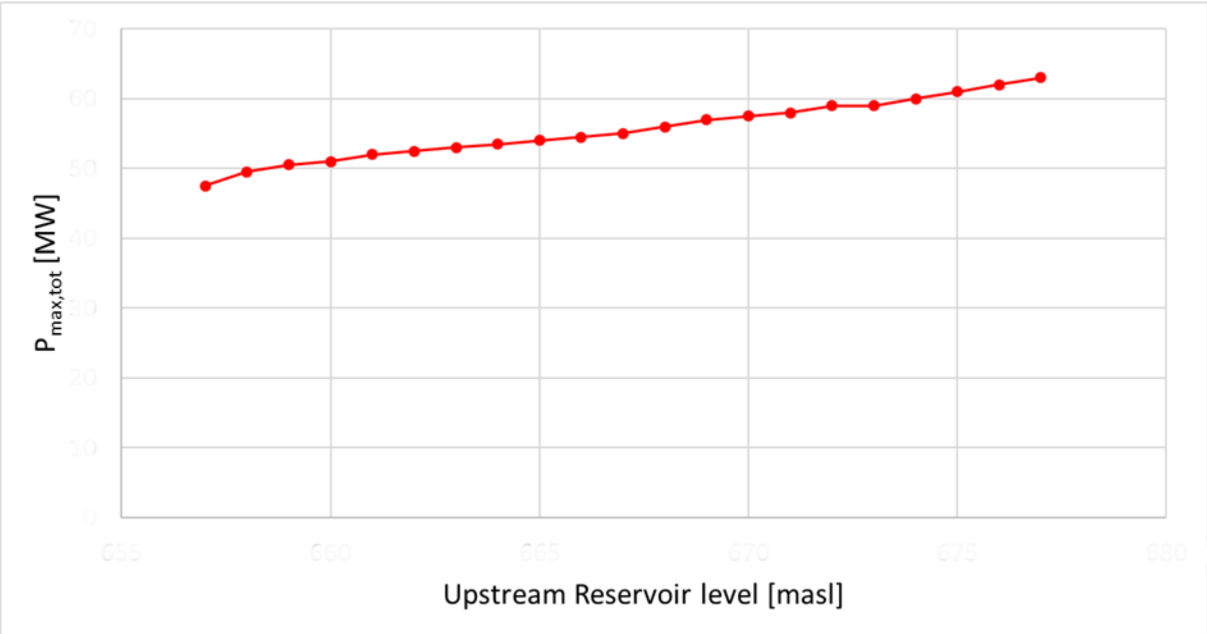


Figure 57 Maximum power set point for the hydro power plant as function of the water level.

5.3.2 Description of the renovation options

The renovation options are to update the 3 oldest units. The following configurations are possible and will be compared in this study case:

- **4 Francis turbines:** Update the 3 old units. The unit #3 is not modified. For this option, the inlet pipes are kept.
- **3 Francis turbines:** Update the unit #4 and replace the two other units by only one unit of 30 MW. For this new unit, the inlet pipe diameter is increased. The unit #3 is not modified.
- **2 Francis turbines:** Replace the 3 old units by a new one of 45 MW. For this new unit, the inlet pipe diameter is increased. The unit #3 is not modified.

One of the modules of the RENOVHydro library allows the sizing of renovation options for civil and electromechanics domains and the estimation of the costs generated. For this case, the following prices are estimated:

- The cost of the unit takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications.
    - **4 Francis turbines:** The total cost is in the range of **25.0 MCHF**.
    - **3 Francis turbines:** The total cost is in the range of **23.0 MCHF**.
    - **2 Francis turbines:** The total cost is in the range of **23.2 MCHF**.

5.3.3 Conclusion of this test case

The current values of the performance indicators are set as references and noted 'REF' in the Figure 58. By comparing the different configurations, the configuration with 3 Francis turbines offers two main advantages: the maximum annual revenue (+4.12%) and the cheapest cost. However, reducing the number of units makes it difficult to organize maintenance periods. Therefore, the best economic option shall be carefully evaluated considering maintenance periods and possible outage over the whole concession duration.

Finally, the modifications of the nominal power of the units, the negotiation after the end of the hydraulic concession or a government assistance are linked to economic and legal aspects out of the scope of this first study. These indicators only highlight the value of this renovation option and the usefulness of further study.

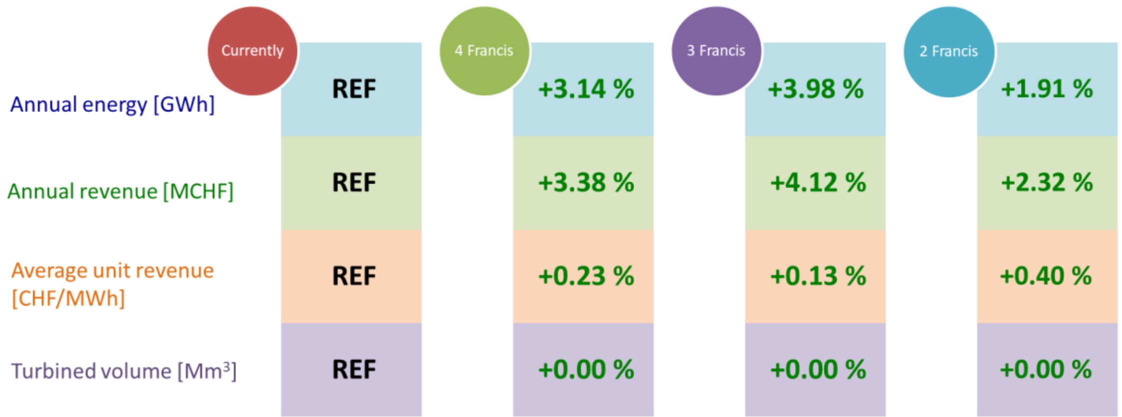


Figure 58 Comparison of the performance indicators between the current situation and the renovation options.

5.4 Renovation option for the test case 7

The 5 units of this power station are very old and will soon be replaced to reduce the maintenance periods and to ensure the sustainability of the hydro power plant. With the systematic approach proposed by RENOVHydro library, it is possible to compare a layout with 2 units, 3 units and 5 units and thus determine which configuration would provide the higher annual revenue. Moreover, due to a sediment deposition in the gallery, 3 different head losses (3 mWC, 6 mWC, 9 mWC) were taken into account for each unit configuration. Finally, 2 different dam elevations were investigated to determine if the increase of the storage capacity is interesting for this hydraulic power plant according to the water inflow.

To answer these questions, the current situation will be first analyzed with the RENOVhydro library to determine the annual revenue obtained with this hydraulic power plant and the cost of these electromechanical and civil options. Then, the attractiveness of each renovation option will be quantified with the performance indicators. Finally, this analysis with 27 different renovation options is the perfect candidate to compare the consuming time with and without the RENOVHydro library.

5.4.1 Current situation

According the methodology used in the RENOVHydro library, the complete analysis of a hydraulic power plant requires the following information:

- A SIMSEN model of the hydraulic power plant was created. The power utility provided all the geometry of the waterway and the rated values of the Francis turbines. With these data, the complete numerical model was created. The total inertia, the reference diameter of the turbine and the performance hill chart were estimated by the new RENOVHydro library.
- The water inflow and the electricity price time history of the year 2017 were also provided by the power utility.
- A minimum and maximum water level are defined for the upstream reservoir and illustrated in Figure 59.
- A released flow in normal operating conditions is applied, see Figure 60.
- A maximum power set point for the hydro power plant as function of the water level is defined for the upstream reservoir, see Figure 61.
- The variation of volume of the upstream reservoir according the water elevation can be approximated with a trapezoid, see Figure 62.

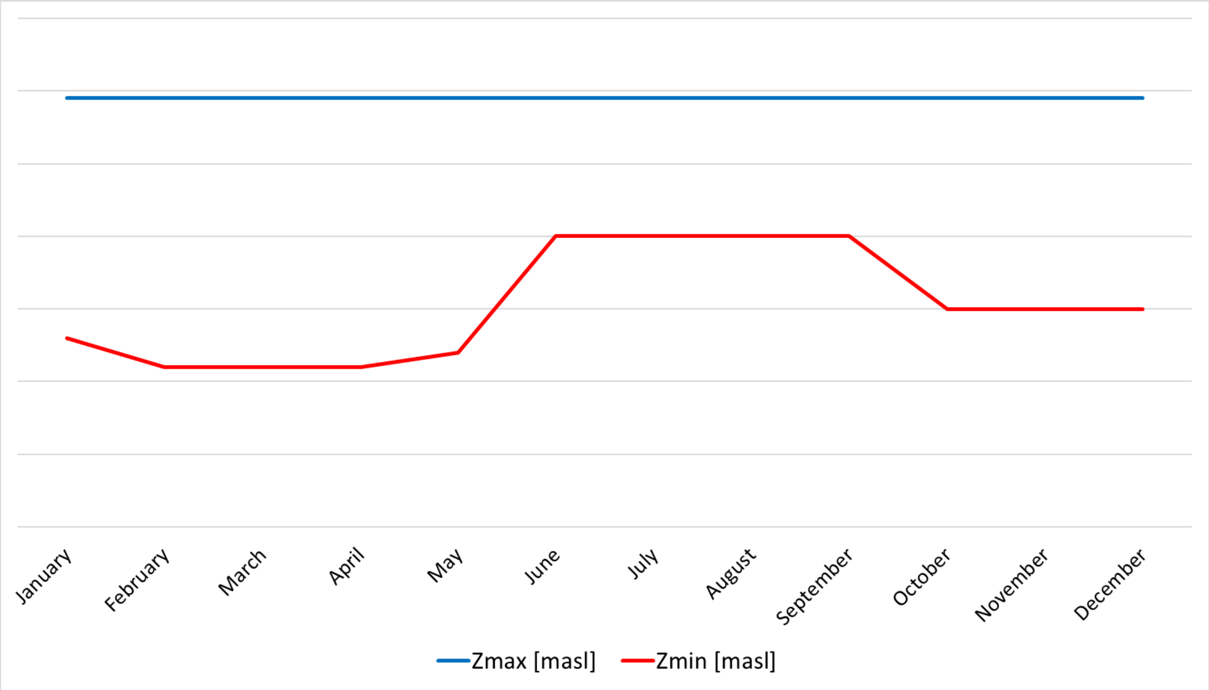


Figure 59 Minimum and maximum water levels in the upstream reservoir throughout the year.

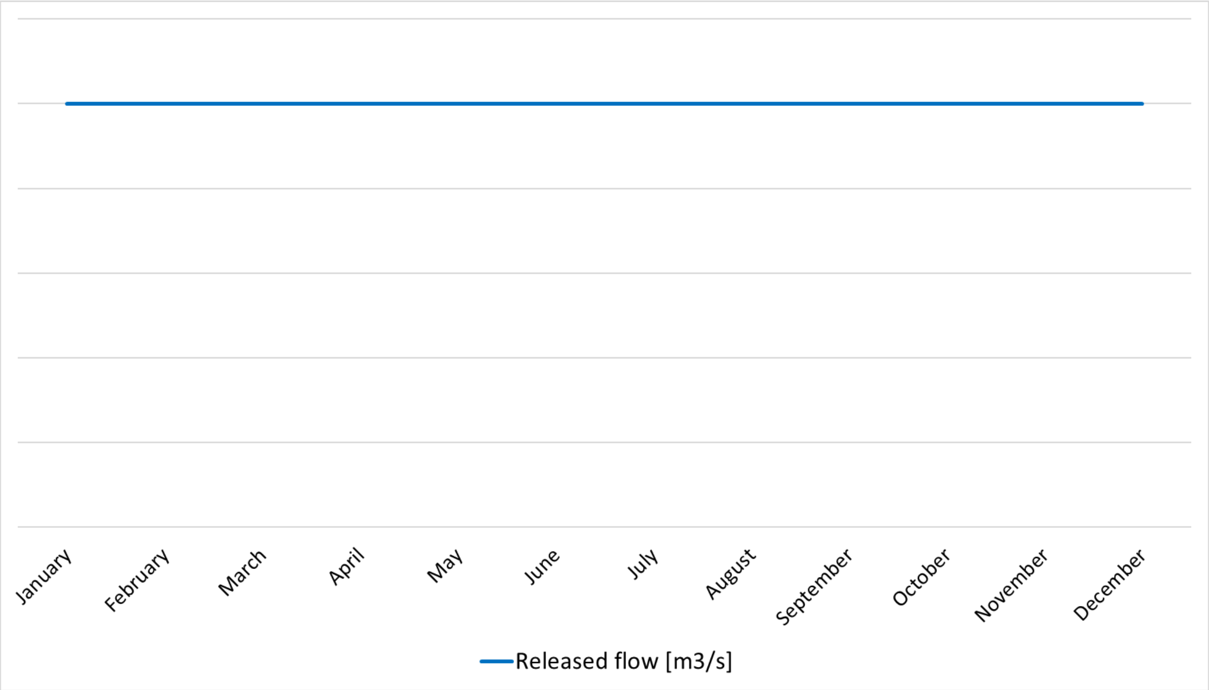


Figure 60 Released flow throughout the year.

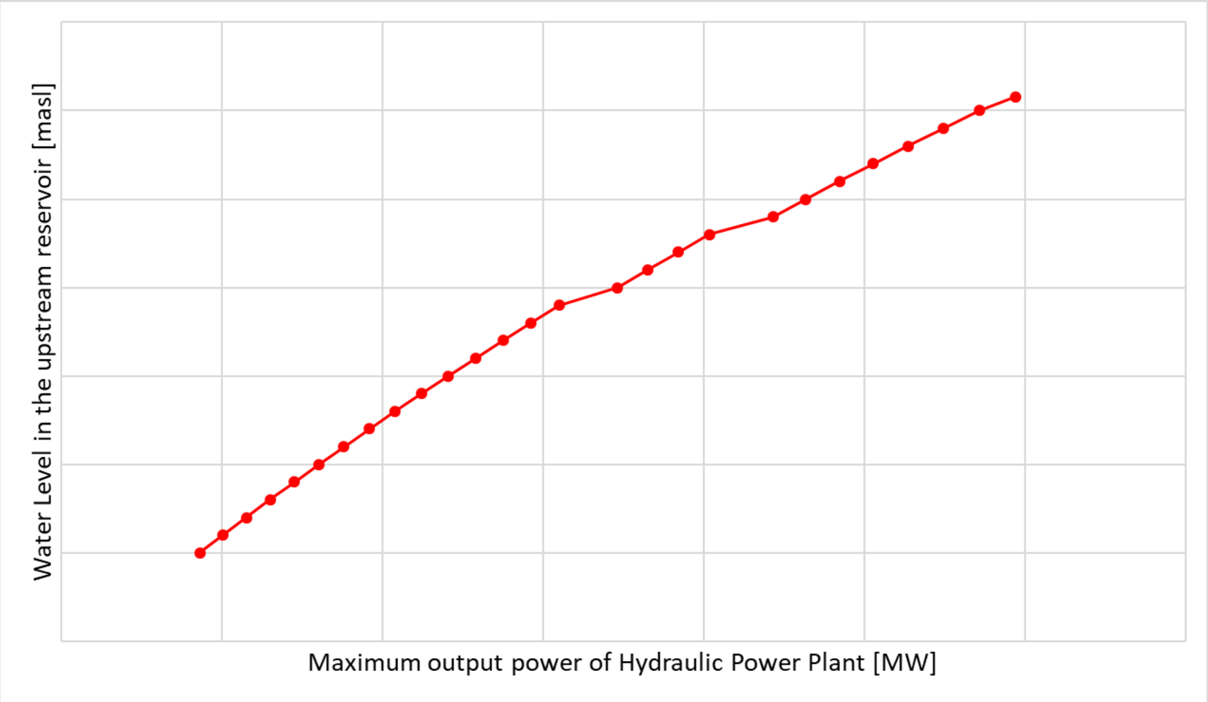


Figure 61 Maximum power set point for the hydro power plant as function of the water level.

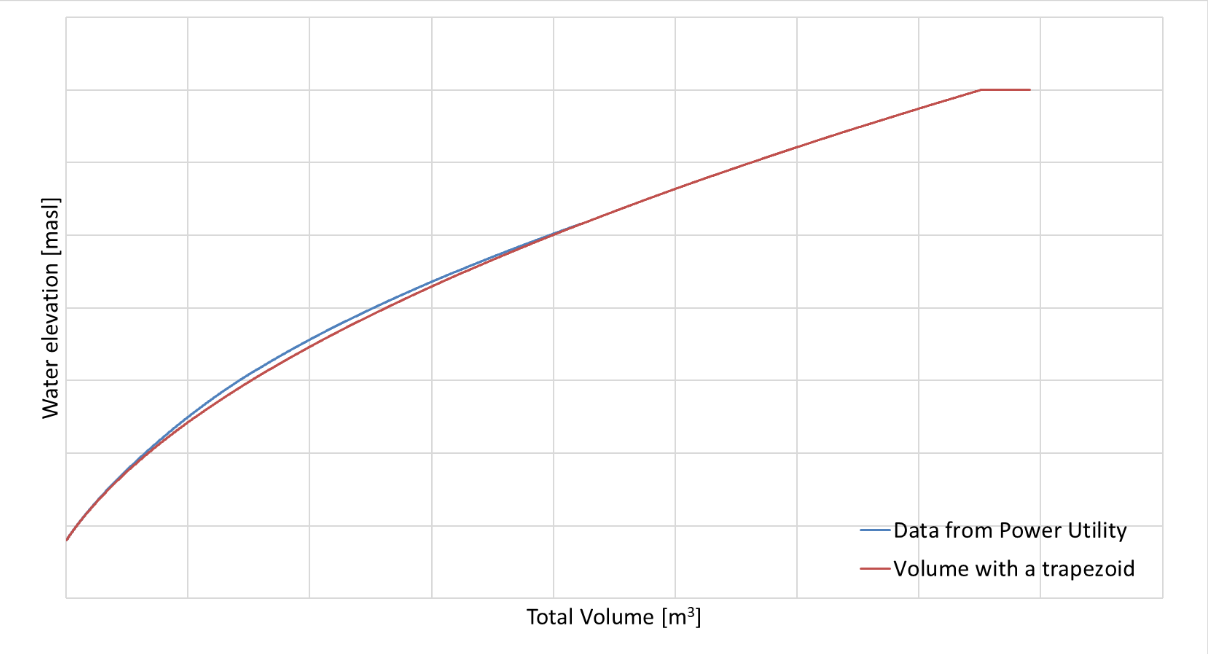


Figure 62 Current volume as function of the water elevation. The variation of the volume can be defined by a trapezoid.

5.4.2 Description of the renovation options (first step)

The first step of the analysis is the upgrade of the current units. The following configurations are possible and will be compared in this study case:

- **5 Francis turbines:** For this option, the rated power of each unit is still equal to 5 MW. The inlet pipes are kept.
- **3 Francis turbines:** The 5 units are replaced by 3 other units of 8.3 MW each. For these new units, the inlet pipe diameter is increased.
- **2 Francis turbines:** The 5 units are replaced by 2 other units of 12.1 MW each. For these new units, the inlet pipe diameter is increased.
- These 3 configurations will be compared for 3 different energy losses in the gallery imposed by the sedimentation volume: Δh_r= +3 mWC **/** Δh_r= +6 mWC **/** Δh_r= +9 mWC.

One of the modules of the RENOVHydro library allows the sizing of renovation options for civil and electromechanics domains and the estimation of the costs generated. For this case, the following prices are estimated:

- The cost of the unit takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications.
  - **5 Francis turbines:** The total cost is in the range of **14.0 MCHF**.
  - **3 Francis turbines:** The total cost is in the range of **15.5 MCHF**.
  - **2 Francis turbines:** The total cost is in the range of **13.0 MCHF**.

5.4.3 Conclusion of this first step

For each energy losses in the gallery, the values of the performance indicators for 5 units are set as references and noted 'REF' in the Figure 63, Figure 64 and Figure 65. By comparing the different configurations, the configuration with 2 Francis turbines offers two main advantages: the maximum annual revenue and the cheapest cost. Moreover, the sediment deposit in the gallery increases the energy losses and reduces the annual revenue of 3.6%. It would be interesting to compare this annual revenue reduction with the cost of removing sediment and stopping the hydro power plant during this maintenance period.

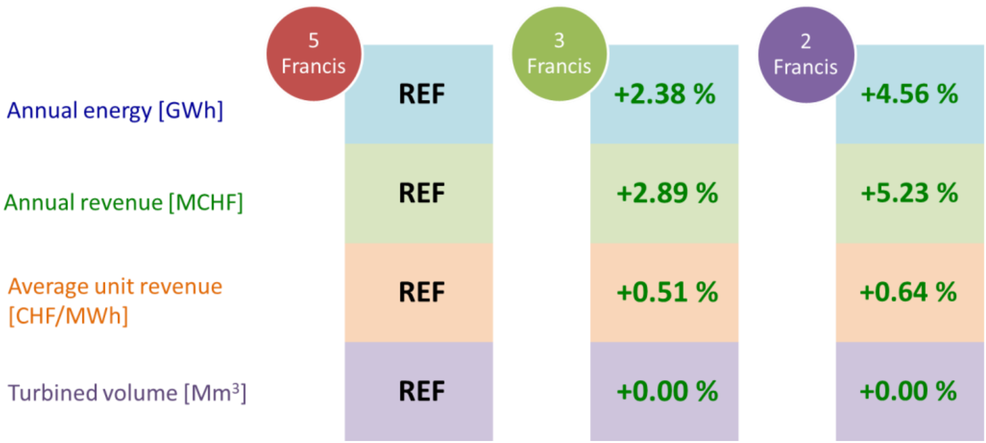


Figure 63 Comparison of the performance indicators between the current situation (5 Units) and the renovation options for head losses Δh_r= +3 mWC.

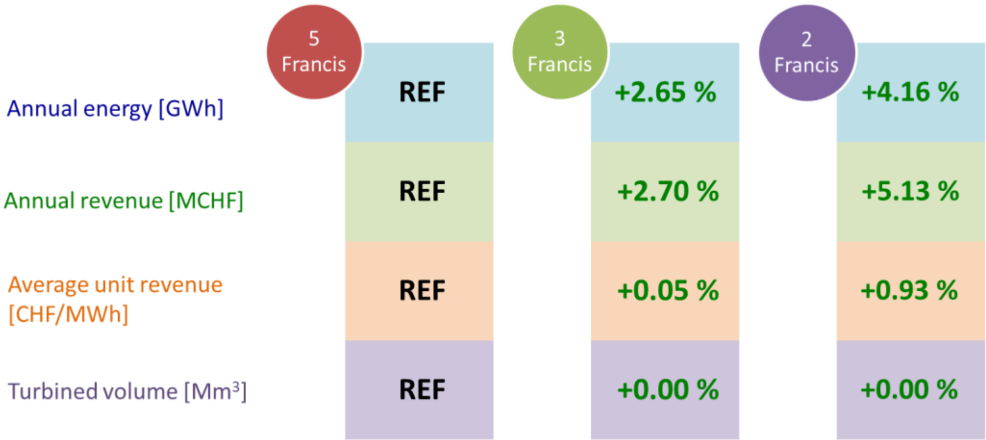


Figure 64 Comparison of the performance indicators between the current situation (5 Units) and the renovation options for head losses Δh_r= +6 mWC.

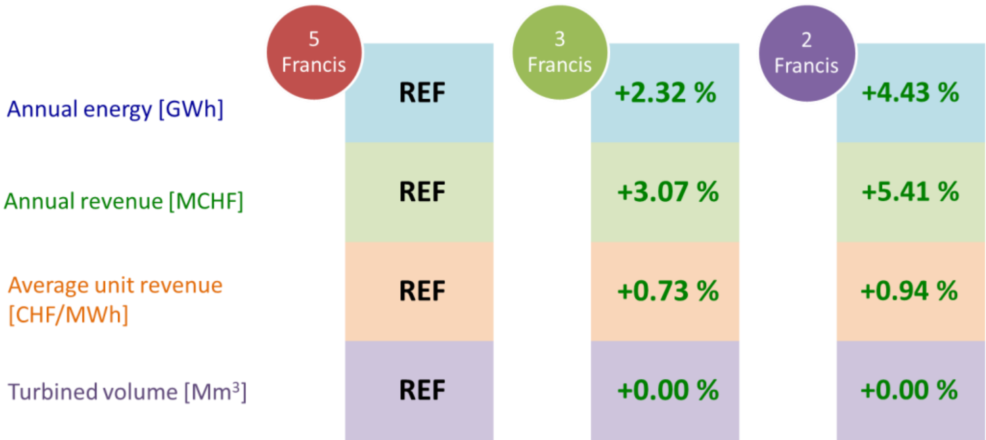


Figure 65 Comparison of the performance indicators between the current situation (5 Units) and the renovation options for head losses Δh_r= +9 mWC.

5.4.4 Description of the renovation options (second step)

The second step of the analysis consists in raising the dam height by 10m or 20m for the reservoir expansion. The main modifications are the following:

- Increase of the maximum water level: +10m or +20m.
- Increase of the effective storage volume by a factor 2 or 3, respectively.
- Increase the rated head of each unit → New Francis turbines.

One of the modules of the RENOVHydro library allows the sizing of renovation options for civil and electromechanics domains and the estimation of the costs generated. For this case, the following prices are estimated:

Dam elevation: +10m

- With a length of crown of the dam fixed to 110 m, the new concrete volume is in the range of 18’000 m³. The concrete price is fixed to 500 CHF/m³. Considering the cost for the site installation, contingency costs, engineering fees and general expenses, the cost of the civil modification is in the range of **12.6 MCHF**.
- The cost of the unit takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications.
    - **5 Francis turbines:** The total cost is in the range of **14.0 MCHF**.
    - **3 Francis turbines:** The total cost is in the range of **15.3 MCHF**.
    - **2 Francis turbines:** The total cost is in the range of **13.0 MCHF**.

Dam elevation: +20m

- With a length of crown of the dam fixed to 110 m, the new concrete volume is in the range of 42’000 m³. The concrete price is fixed to 500 CHF/m³. Considering the cost for the site installation, contingency costs, engineering fees and general expenses, the cost of the civil modification is in the range of **29.4 MCHF.**
- The cost of the unit takes into account the cost of the electromechanics (turbines, governors, generator, transformer, auxiliary systems, …) but not the civil modifications.
    - **5 Francis turbines:** The total cost is in the range of **13.0 MCHF**.
    - **3 Francis turbines:** The total cost is in the range of **15.0 MCHF**.
    - **2 Francis turbines:** The total cost is in the range of **12.0 MCHF**.

5.4.5 Conclusion of this second step

As for the first step, the renovation option with 2 units is always the most advantageous, both in terms of price and annual revenue, whatever the dam elevation. The Figure 66 and Figure 67 summarizes the performance indicators only for the case with an energy losses equal to +6 mWC in the gallery. Finally, to determine if the increase of the storage volume is interesting, it is important to extend the study over the concession period. Indeed, the amount of water available over the next decades is a key factor that has a strong impact on the future performance of the hydraulic power plant. The study of the impact of the political, economic and environmental contexts on the best technical solutions for hydropower plant renovation is the main goal of another project named SHAMA, also funded by the SFOE [16].

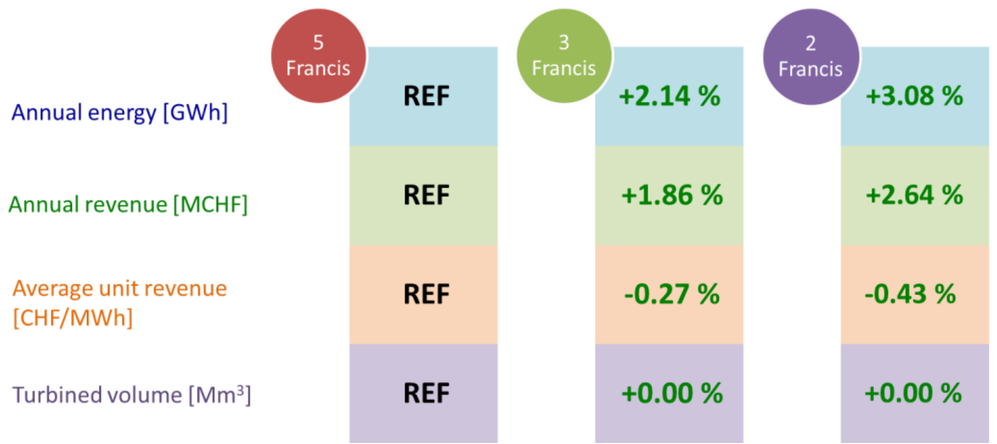


Figure 66 Comparison of the performance indicators between the current situation (5 Units) and the renovation options for head losses Δh_r= +6 mWC and the dam elevation +10m.

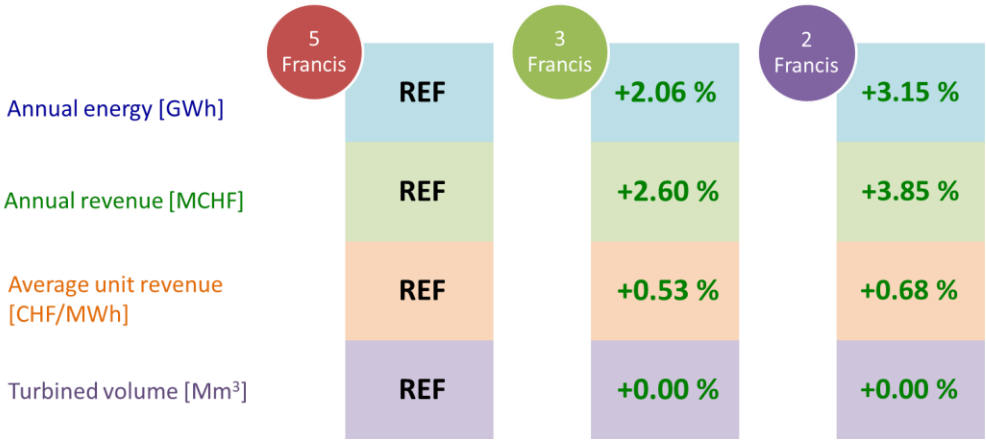


Figure 67 Comparison of the performance indicators between the current situation (5 Units) and the renovation options for head losses Δh_r= +6 mWC and the dam elevation +20m.

5.4.1 Conclusion of this test case

For this test case, 27 different renovation options were analyzed in details with the RENOVHydro library: 3 configurations of units, 3 energy losses in the gallery and 3 different dam elevations. The systematic analyses highlighted that a configuration with 2 units offers a higher annual revenue at a lower cost. However, reducing the number of units makes it difficult to organize maintenance periods. Therefore, the best economic option shall be carefully evaluated considering maintenance periods and possible outage over the whole concession duration. Moreover, the modifications of the nominal power of the units, the negotiation after the end of the hydraulic concession or a government assistance are linked to economic and legal aspects out of the scope of this first study. These indicators only highlight the value of this renovation option and the usefulness of further study.

Finally, after gathering all the information on the hydraulic power plant, the systematic approach proposed by the RENOVHydro project for this test case significantly reduces the consuming time to study the different renovation options by a factor 15, see Table 1.

- The preparation of the SIMSEN model (creation of a new performance hill chart for each renovation option, specifications and price estimation, …) was performed in only 1 hour with the new databases and the automatic procedures, instead of 5 days with the manual approach.
- The scenario performance assessment (creation of the hydraulic performance tables, simulation of a reference year, computation of the performance indicators) was performed in 1 day with the automatic management of the SIMSEN models and the Mixed-Integer Linear Programming algorithm instead of 14 days with the manual approach.
- The ancillary services (assessment of realistic primary and secondary control potential) was performed in 1 day instead of 14 days with the manual approach.

Table 1 Comparison of the consuming time with and without the RENOVHydro library.

	Analysis with the current tools	Analysis with the RENOVHydro library
Preparation of the SIMSEN model	5 days	1 hour
Scenario performance assessment	14 days	1 day
Ancillary services	14 days	1 day
Total hours	**264**	**17**

6 Conclusions

The renovation of hydroelectric power plant is multidimensional decision-making process made-up of a number of aspects at different levels such economic and technical. With the RENOVHydro project, the decision-making process for the renovation of hydropower plants is simplified with 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, return on investment and ancillary services for each renovation option can be analysed to identify the technical trends according to a given political, economic and environmental context. The RENOVHydro methodology is divided into 4 distinct parts:

- The 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. The performance hill chart is essential to ensure the accuracy of the analysis of the different renovation options. Thus, as this information is rarely known by the user and more importantly for a new unit, an empirical model was developed to define hydraulic performance hill charts for hydraulic turbine according to the value of the speed factor, the discharge factor and the year of commissioning. The automatic creation of a performance hill chart for 3 types of hydraulic machines (Francis turbines, Pelton turbines and pump-turbines) was validated with a comparison of the transient behavior after an emergency shut down.

  After selecting the reference numerical model, civil engineering and hydroelectric renovation options can be selected with a new Graphical User Interface guiding the user in providing a formal specification of electromechanical and civil engineering options. According to the renovation options, the specification 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 renovation option is also estimated.

  With these new databases for Francis, Pelton and pump-turbines, the new Graphical User Interface and the automatic specifications and cost estimation, the preparation time of the different renovation options is significantly reduced.

- 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 automatic management of the SIMSEN models simplifies the determination of the best performance of the hydraulic power plant and therefore the refinement of the hydraulic performance table can be greatly increased compared to a manual approach.

- The simulation of a complete year is developed in the third part of the RENOVHydro methodology by using the hydraulic performance table computed previously. 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 option, a mathematical optimisation approach is used with a Mixed-Integer Linear Programming algorithm to maximize the annual revenue. This mathematical approach has the advantage of maximizing the annual revenue (objective function), regardless of the technological option chosen.

Moreover, the MILP energy dispatch model can also be extended to include revenues and constraints associated with ancillary services provision. An application of this new algorithm to a large storage power plant highlighted that the ancillary services provisions can correspond to 44% of the annual revenue and thus represented a very interesting financial part for the power utilities.

The automatic management of the SIMSEN models to compute the hydraulic performance table and the new MILP algorithm drastically reduced the analysis time and allowed to compare the best performance of each renovation option.

- With transient simulations, the ancillary services and the flexibility of production is quantified and the realistic primary and secondary control potential can be assessed. In order to automatically assess the primary control potential of the renovated hydroelectric power plant, a simple and robust methodology to deduce the parameters of a PID controller were developed. Moreover, with the FMI co-simulation protocol implementation in the RENOVHydro library, co-simulations between SIMSEN and EMTP-RV can be performed to simulate detailed hydro units in SIMSEN with a detailed transmission line and grid in EMTP-RV.

Finally, the RENOVHydro project made it possible to compare different renovation options for combinations of different renovation options. This systematic approach objectively compares the best potential of each renovation option and determine their interest over a typical year of operation. This approach is particularly interesting with relatively low electricity prices and increasingly alarming global warming. In this document, 4 case studies have been described in detail: two with run-of-river power plants and two with a storage power plant. For one of these test cases, 27 renovation options were compared and with the systematic approach proposed by the RENOVHydro project, the consuming time was reduced by a factor 15.

Moreover, this systematic approach is also very important because each hydraulic power plant is unique both in terms of its technical characteristics and its legal and economic situation. This is why the performance indicators computed only highlight a possible valuation of the potential energy available and the usefulness of further study. The economic and legal aspects, such as subsidies, government assistance, concession renegotiation, are out of the scope of this first study and must be handled by engineers specialized in these fields.

7 Outlook and next steps

The 20-20-20 strategic energy policy decided by the European Union and its accompanying Renewable Energy Directive is leading toward a large electric energy system transition. The two major pillars of this transition are:

- a massive penetration of alternative renewable energies,
- a broad deployment of energy efficiency initiatives and technologies.

In this context, 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 renewable energies needs substitution and storage capabilities that hydropower can offer.

A first solution to absorb the stochastic variations of the renewable energy is pumped storage power plants. This type of power plant is not yet included in the MILP optimization algorithm that simulates a typical year of turbine operation. This new option is important for the future because the stability of the electricity grid will be one of the biggest challenges of the coming years.

A second solution to contribute to power network reliability is the primary and the secondary frequency control services. All generating units that supply to the electricity market must demonstrate the compliance with Transmission System Operators, TSO. Thus, a provider of primary control, also called Frequency Containment Reserve FCR, has to offer both positive and negative control power at any time for a stable and secure operation of the grid. The revenue and constraints associated with ancillary service provision are already implemented in the MILP algorithm. Moreover, the PID parameters of the control system was validated only for the primary control capability defined by the Swiss TSO. This approach should be extended to other European countries to make the RENOVHydro library more attractive.

Finally, the performance indicators currently calculated for each renovation option are simplified. More realistic economic models could be added to better match the studies already carried out by power utilities. The addition of an economic model for long-term investments would be a plus to analyze the renovation options over the concession period.

8 National and international cooperation

The RENOVHydro project has created a synergy with several important actors in the research and development of hydropower in Switzerland:

- **EPFL-LMH laboratory** has acquired a well-known reputation of independent expertise in the field of experimental validation of hydraulic performances of reduced physical scale model of turbines, pumps and pump-turbines. EPFL-LMH is one of the participating institutes of SCCER-SoE and Prof. François Avellan, the head of EPFL-LMH, is the deputy head of this center, ensuring a link of the RENOVHydro Project research activities with the others SCCER-SoE research projects. Moreover, the RENOVHydro Project is co-funded by the CTI/KTI and the SFOE where Prof. Mario Paolone from EPFL-DESL Laboratory is also a project Partner, and is the head of the SCCER-Furies program.
- **Power Vision Engineering Sàrl** is a member of Swiss Competence Center on Supply of Electricity (SCCER-SoE) and participate to SCCER-SoE events. Power Vision Engineering Sàrl is also a member of IEC Technical Committee 4 who develops and maintains International Standards and reports for hydraulic rotating machinery and associated equipment allied with hydropower development. Power Vision Engineering Sàrl is also a partner together with the EPFL as well as both academic and industrial European partners of a European Research Project HYPERBOLE, part of FP7 Energy program and is involved in tasks related to control services optimization and hydropower plant contribution to grid stability with INESC Porto (Portugal).
- The **Power Utilities** provided real test cases of Swiss hydropower plants as well as electricity market and hydrology competences to establish and validate methodologies. Such synergies provide a high agility and cover all need competences to achieve the project.

Finally, the RENOVHydro project benefited from the international collaborations of Power Vision Engineering Sàrl and of the EPFL-Laboratory for Hydraulic Machines, which also represents potential ways for the project dissemination. Indeed, Switzerland is at the center of Europe and is strongly influenced by the political and economic decisions of its neighboring countries. Consequently, the probabilistic projections taken into account in this project can easily be transposed to the various hydraulic power plants abroad and more particularly in Europe.

9 Publications

9.1 Conference paper and Poster

a) Landry, C., Nicolet, C., Gomes, J., Andolfatto, L., Avellan, F., Todde, C., “Renovation of hydraulic power plant: how to select the best technical options?”, Hydro2018, Gdansk, Poland, October 2018

b) Landry, C., Nicolet, C., Gomes, J., Avellan, F., “Methodology to determine the parameters of the hydraulic turbine governor for primary control”, Hydro2019, Porto, Portugal, October 2019.

c) Landry, C., Nicolet, C., Gomes, J., Andolfatto, L., Avellan, F., Todde, C., Derivaz, J., “RENOVHydro: Development of a Decision-Making Assistant for Hydropower Project Potential Evaluation and Optimization”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018

d) Barnoud, M., Chamoun, S., Manso, P., “Valorisation des mesures de mitigation des éclusées en systèmes complexes : quelle échelle spatiale privilégier ?”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018.

e) Gaertner, V., Chamoun, S., Manso, P., “Les principaux vecteurs d’adaptation d’installations hydroélectriuqes de montagne en Suisse”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018.

f) Giovani, M., Nicolas, A., Manso, P., Schleiss, A., “Rénovation d’aménagements hydroélectriques alpins”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018.

g) Chamoun, S., Manso, P.A., G. De Cesare, Gaertner, V., Crettenand, S., Todde, C., “Improving hydropower flexibility by synergizing independently managed utilities”, Hydro 2019, Porto, Portugal, October 2019.

h) Chamoun, S., Manso, P.A., Barnoud, M., Crettenand, S., Todde, C., “Hydropeaking mitigation measures in the Swiss Upper-Rhone basin”, Hydro 2019, Porto, Portugal, October 2019.

9.2 Internal project presentation

i) Landry, C. and Nicolet, C., “WP1: Validation of the Francis turbine database”, Power Vision Engineering, 2019_02_20_RENOVHydro_WP1_Short_Francis.pptx, February 2019.

j) Landry, C. and Nicolet, C., “WP1-3: Validation of the Pelton database”, Power Vision Engineering, 2019_08_30_RENOVHydro_WP1_Comparaison_Pelton.pptx, August 2019.

k) Landry, C. and Nicolet, C., “WP1-3: Validation of the Pump-Turbine database”, Power Vision Engineering, 2019_11_20_RENOVHydro_WP1_Comparaison_Pump-Turbine.pptx, November 2019.

l) Landry, C. and Nicolet, C., “Etude de rénovation: Aménagement avec capacité de stockage”, Power Vision Engineering, 2019_06_18_RENOVHydro_WP4_Storage_HPP_Test_Case.pptx, June 2018.

m) Bozorg, M., Beguin, A., Allenbach, P., Nicolet, C., and Paolone, M., “WP2: Electrical grid and ancillary services analysis”, Power Vision Engineering, RENOVHydro_WP2_EMTP_co_simulation_FMU_v2.pptx, August 2019.

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15) **Landry, C., Nicolet, C., Gomes, J., Avellan, F.,** “Methodology to determine the parameters of the hydraulic turbine governor for primary control”, Hydro2019, Porto, Portugal, October 2019.
16) **Landry, C. and Nicolet C.**, “Swiss Hydro Asset Modernization Assessment”, Final report, SFOE, SI/501435-01, November 2019.
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24) **Schillinger, M., Weigt, H., Barry, M., Schumann, R.,** "Hydropower Operation in a changing market environment – A swiss case study", SCCER-CREST, WP3, 2017.

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11 Appendices

11.1 Validation for the test case 1

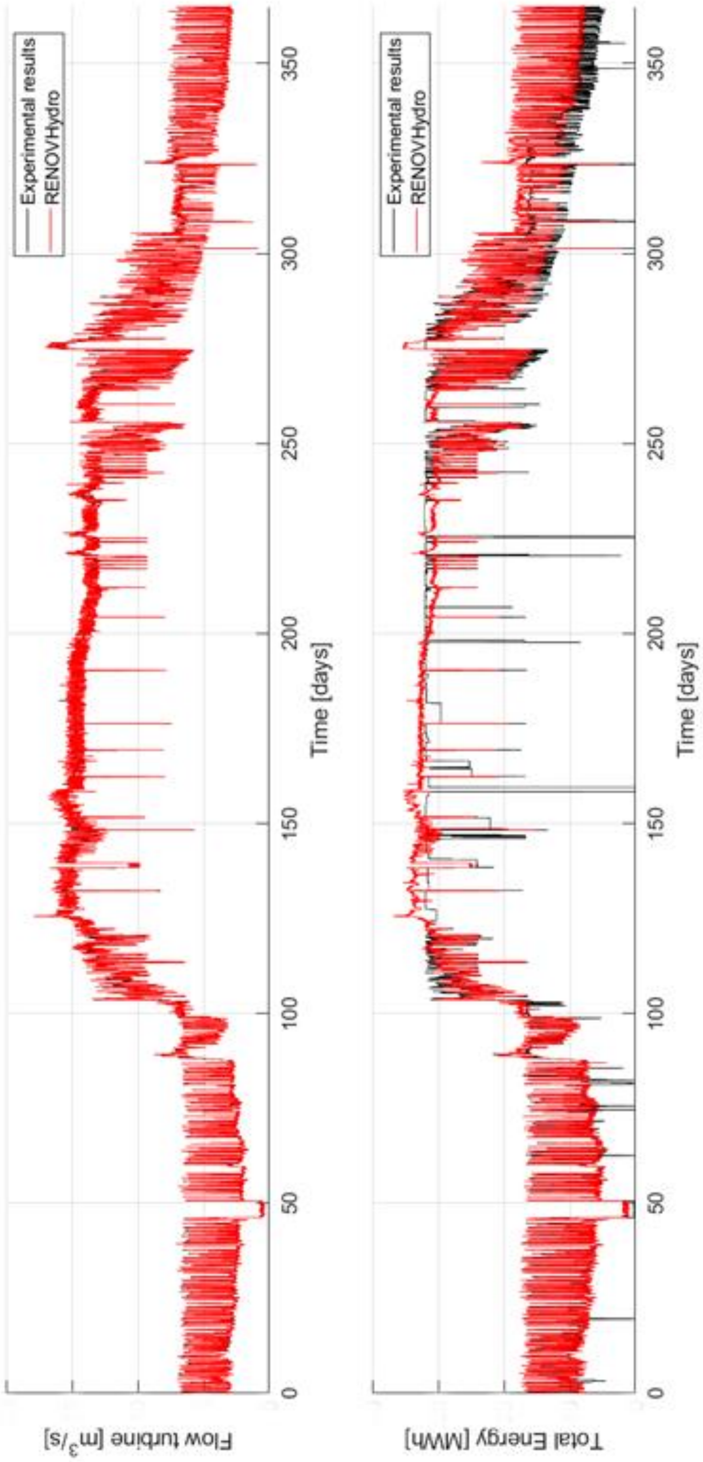

Figure 68 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (black) for the turbined flow and the total energy.

11.2 Validation for the test case 2

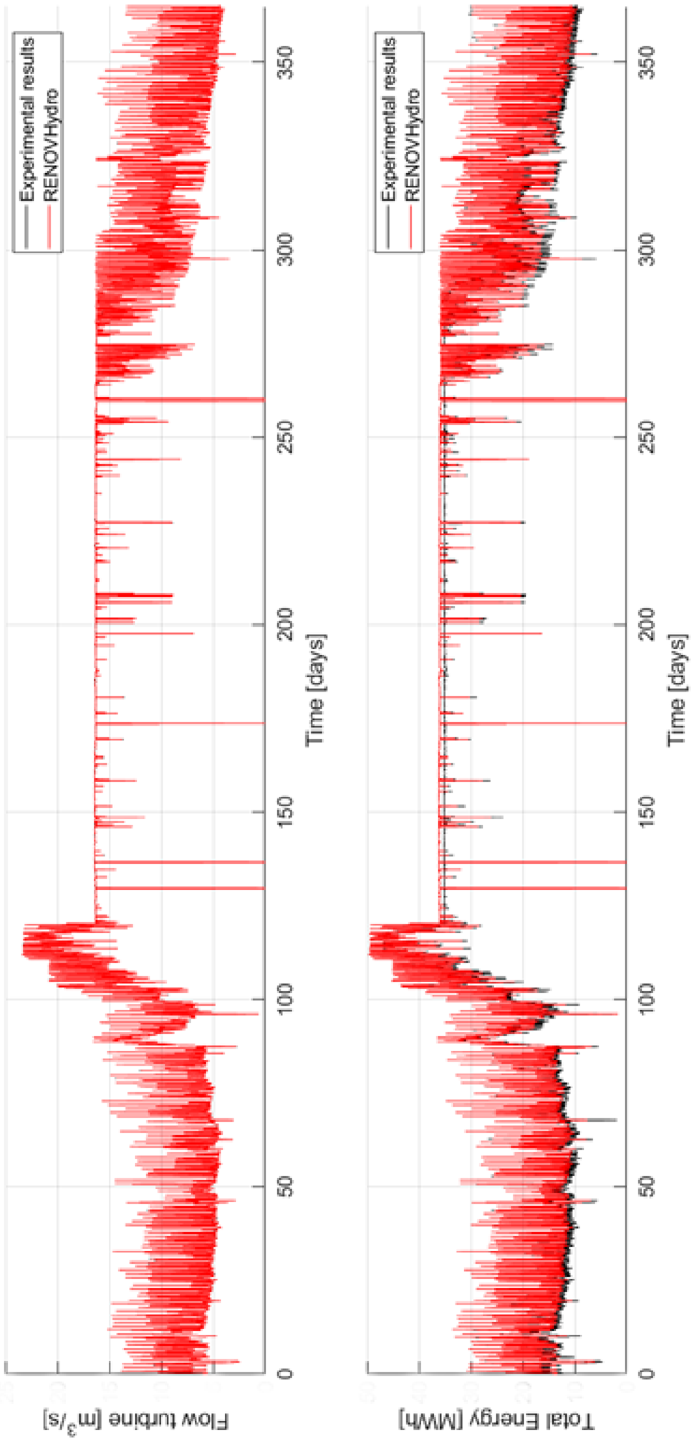

Figure 69 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (black) for the turbined flow and the total energy.

11.3 Validation for the test case 3

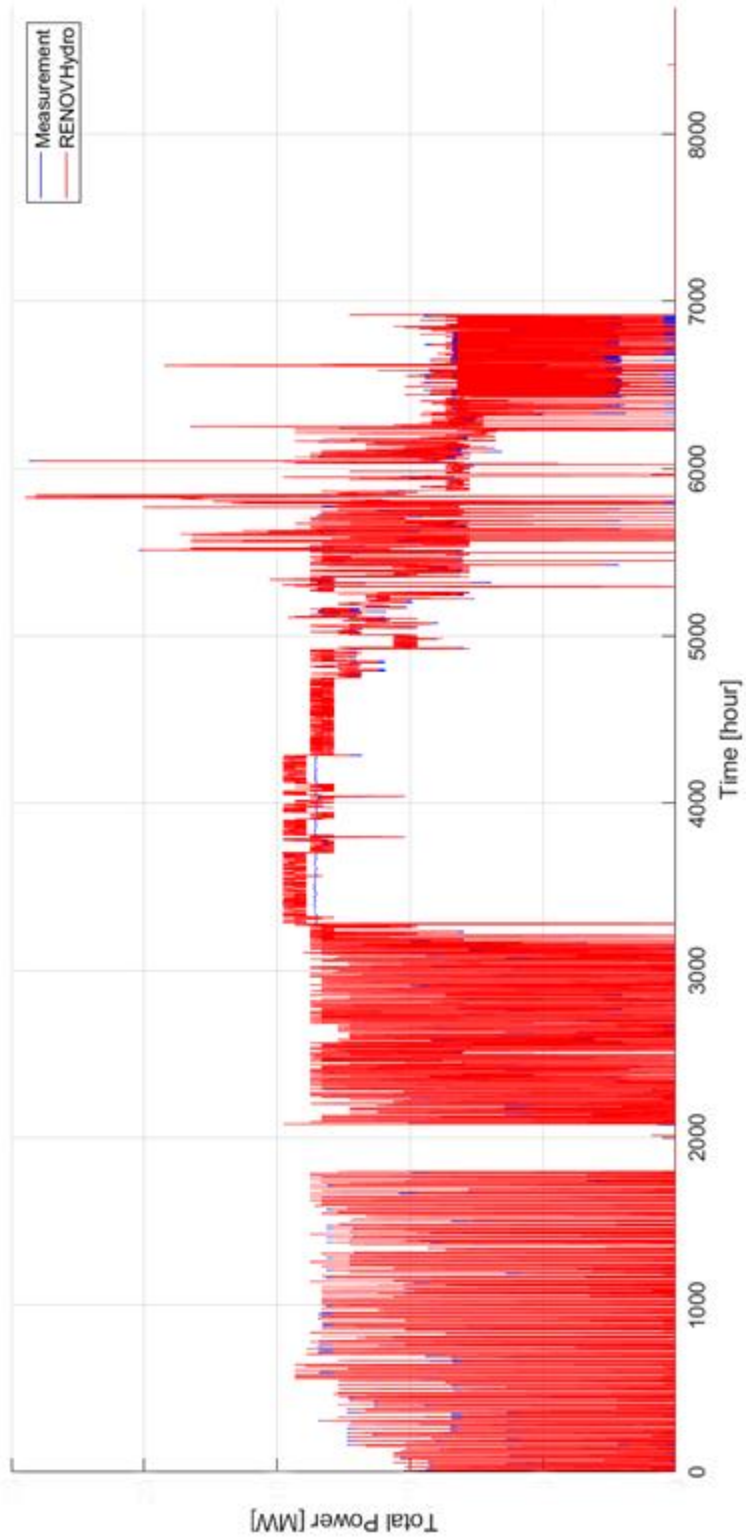

Figure 70 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (black) for the total energy.

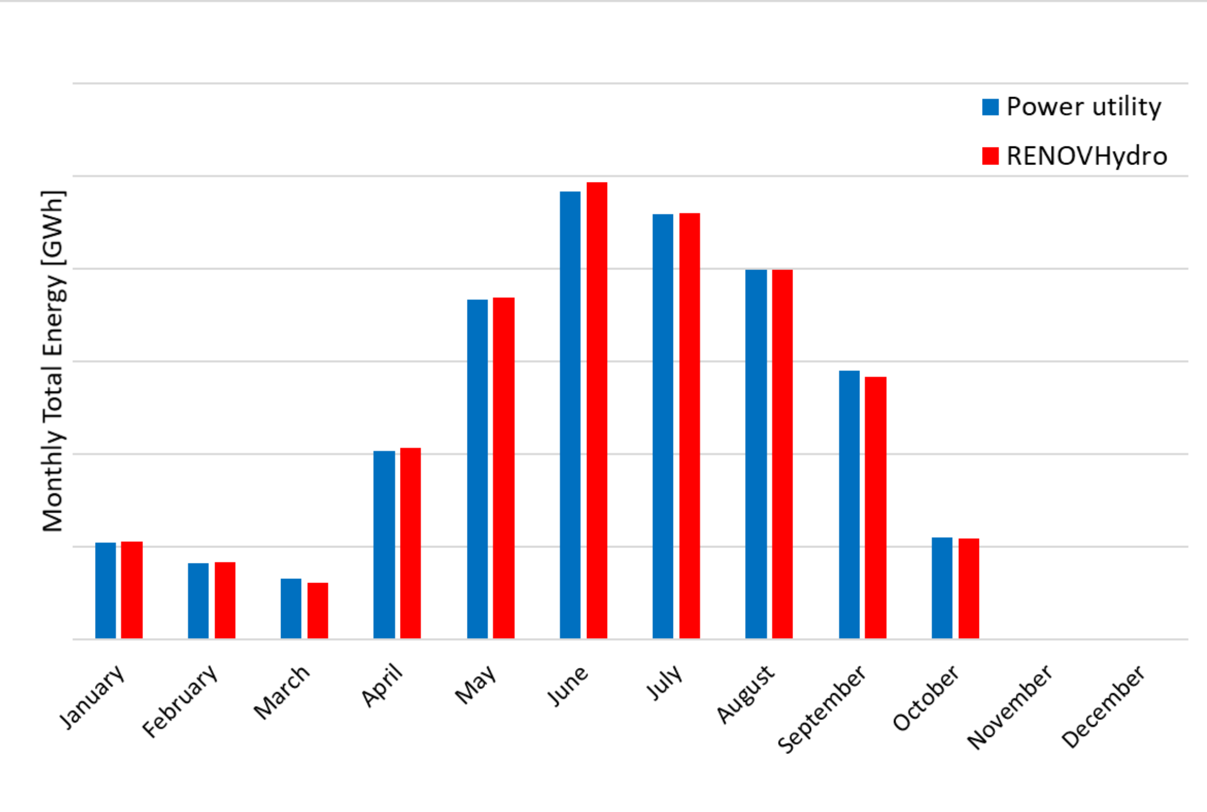

Figure 71 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.

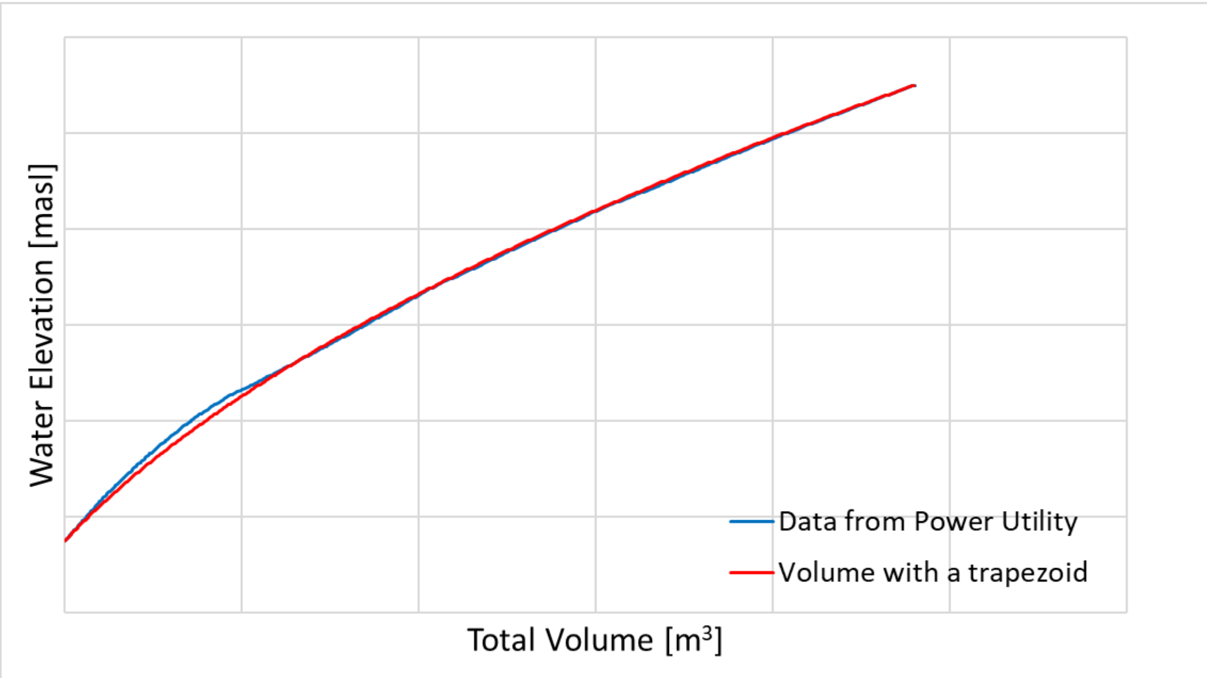

Figure 72 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total volume as function of the water elevation.

11.4 Validation for the test case 4

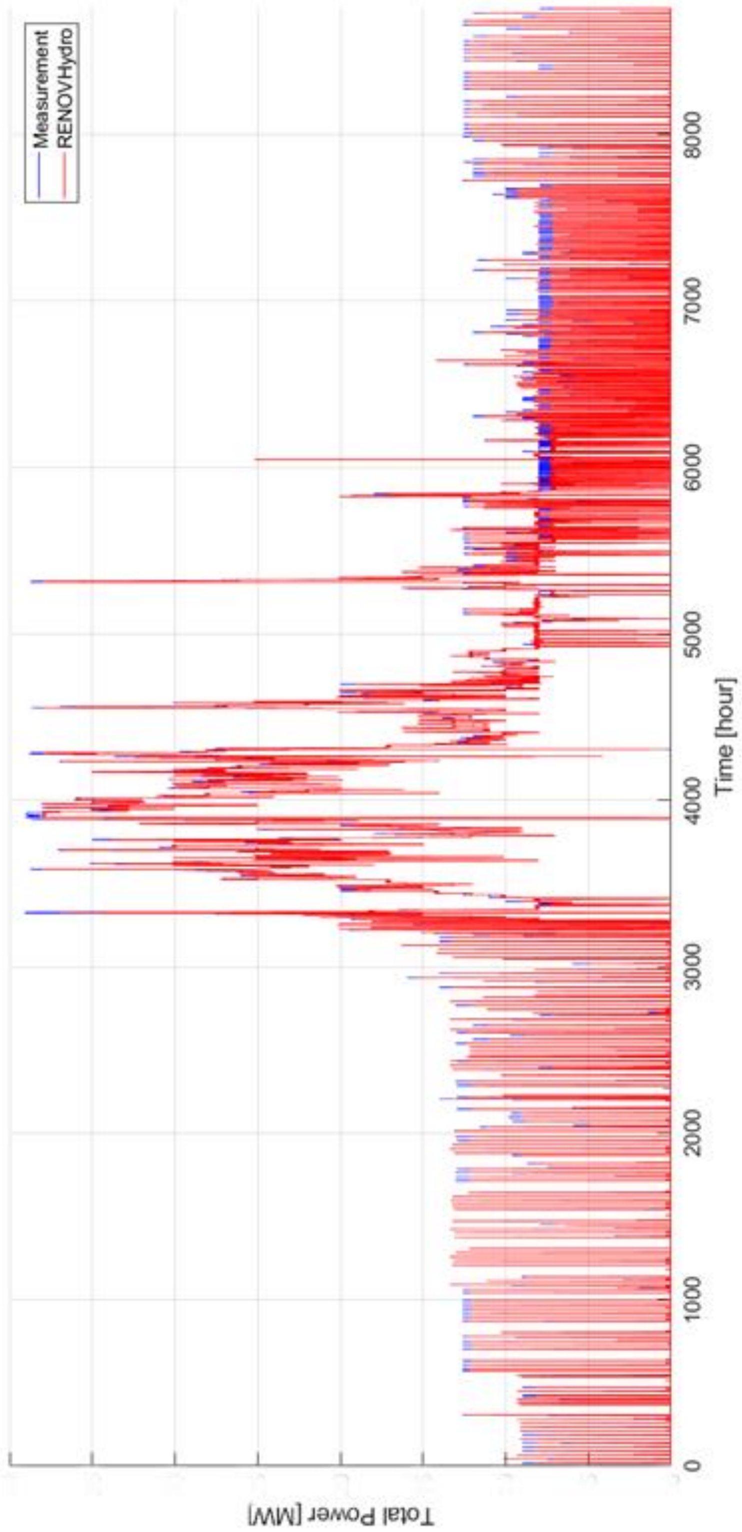

Figure 73 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total energy.

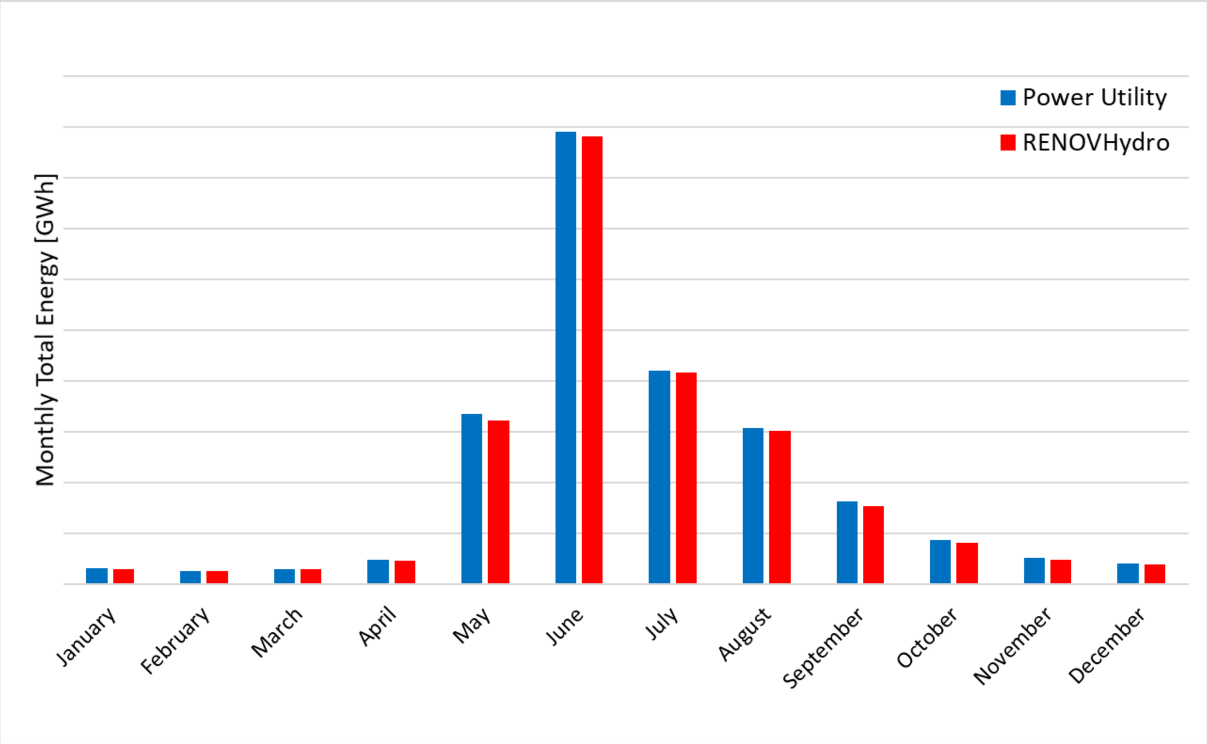

Figure 74 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.

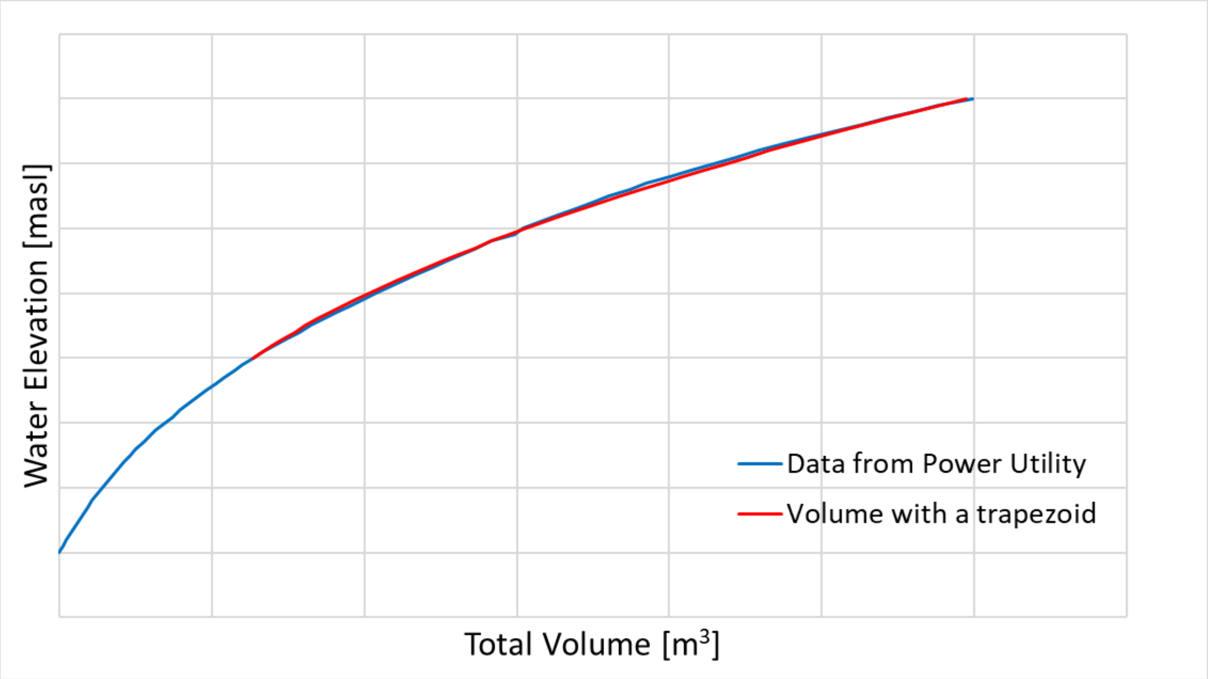

Figure 75 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total volume as function of the water elevation.

11.5 Validation for the test case 5

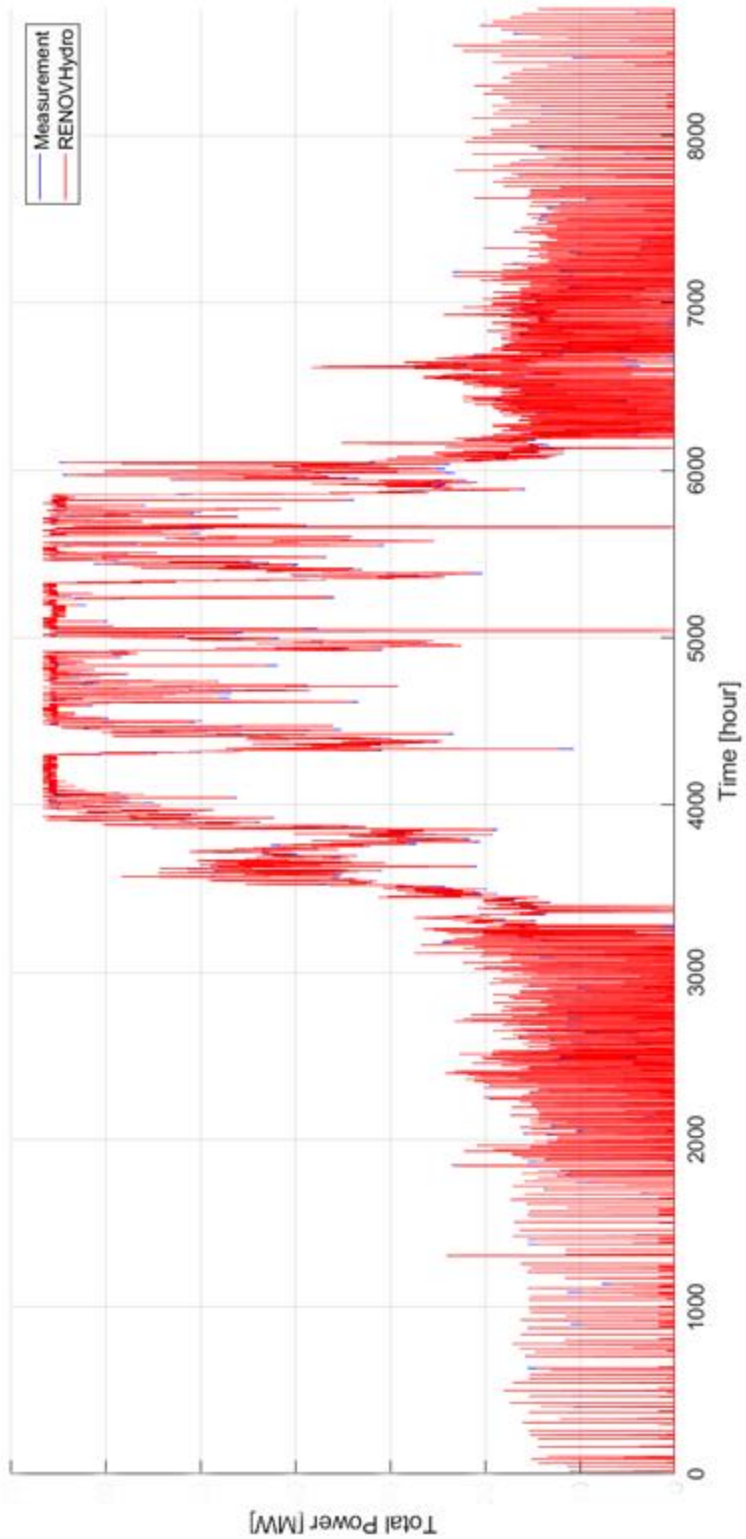

Figure 76 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total energy.

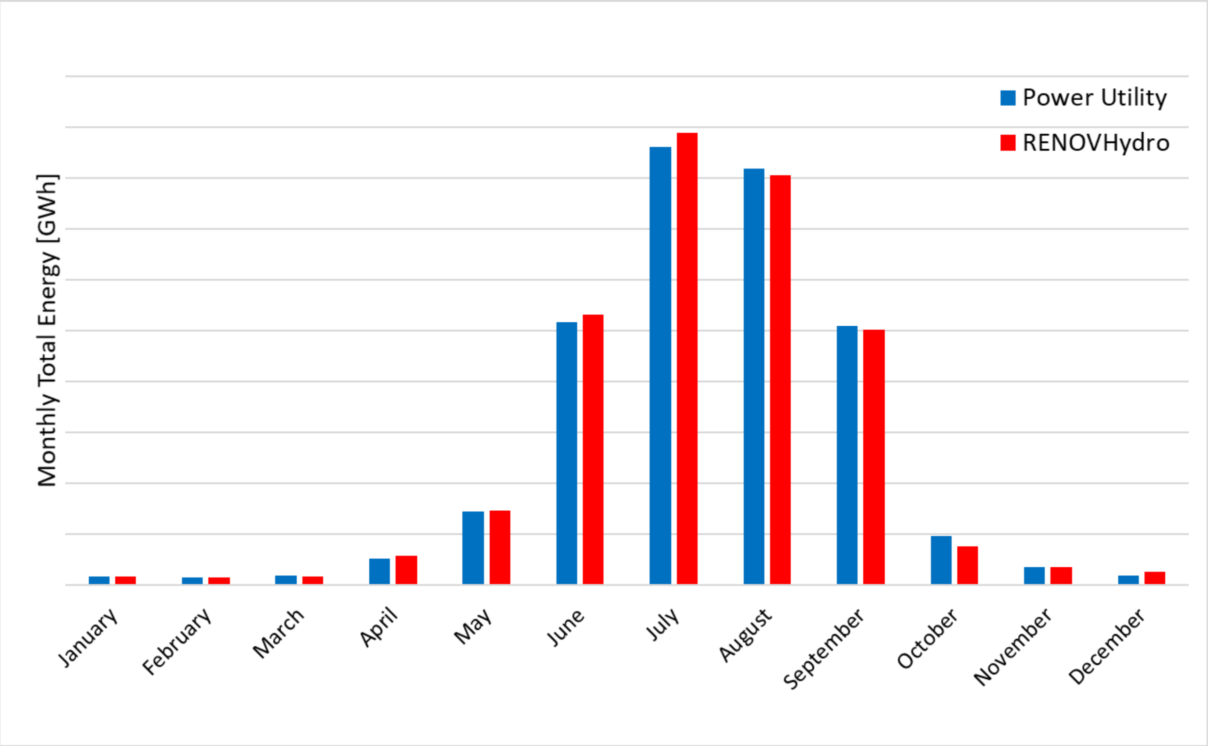

Figure 77 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.