



Final report 04 November 2019

Swiss Hydro Asset Modernization Assessment



Swiss **H**ydro **A**sset **M**odernization
Assessment



Date: 04 November 2019

Location: Ecublens

Subsidiser:

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Section
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:

Power Vision Engineering Sàrl
Chemin des Champs-Courbes 1, CH-1024 Ecublens
www.powervision-eng.ch

Authors:

Dr. Christian Landry, Power Vision Engineering Sàrl, christian.landry@powervision-eng.ch
Dr. Christophe Nicolet, Power Vision Engineering Sàrl, christophe.nicolet@powervision-eng.ch

SFOE project coordinators:

SFOE head of domain: Dr. Michael Moser, michael.moser@bfe.admin.ch

SFOE programme manager: Dr. Klaus Jorde, klaus.jorde@kjconsult.net

SFOE contract number: SI/501435-01

All contents and conclusions are the sole responsibility of the authors.



Summary

The Swiss Hydro Asset Modernization Assessment project (SHAMA) aims at studying the impact of the political, economic and environmental contexts on the best technical solutions for hydropower plant renovation resulting from a systematic assessment process using the RENOVHydro Library. The various Swiss and European political strategies, the evolution of electricity price, climatic changes and environmental constraints are factors that have a direct impact on return on investment of the hydropower renovation for which the best technico-economic solution can be significantly different.

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, ...
- Influence of the electricity market price and hydrology time history in the decision-making process for the next decades.
- Computation of energy and economic indicators to compare the different renovation options.



Contents

1	INTRODUCTION	7
1.1	Background information and current situation	7
1.2	Purpose of the project	9
1.3	Objectives	10
2	PROCEDURES AND METHODOLOGY	11
2.1	Methodology to select the best renovation options	11
2.1.1	Selection of the options	11
2.1.2	Specification	13
2.1.3	Price estimation of the modifications	13
2.1.4	Hydraulic performance table	13
2.1.5	Simulation of an operating year	15
2.1.6	Ancillary services analysis	16
2.2	Hydrology scenarios building	20
2.3	Electricity market scenarios building	22
2.4	Test case modernization potential assessment	25
2.4.1	Test case 1 (Run-of-river power plant)	25
2.4.2	Test case 2 (Run-of-river power plant)	27
2.4.3	Test case 3 (Run-of-river power plant)	28
2.4.4	Test case 4 (Run-of-river power plant)	29
2.4.5	Test case 5 (Run-of-river power plant)	30
2.4.6	Test case 6 (Storage power plant)	31
3.1	Renovation option for the test case 1	32
3.1.1	Current situation	32
3.1.2	Description of the renovation options	34
3.1.3	Water inflow for the next decades	36
3.1.4	Performance indicators over the concession period	38
3.1.5	Electricity market price in 2030	40
3.1.6	Conclusion of this test case	41
3.2	Renovation option for the test case 4	42
3.2.1	Current situation	42
3.2.2	Description of the renovation option	45
3.2.3	Water inflow for the next decades	47
3.2.4	Performance indicators over the concession period	49
3.2.5	Electricity market price in 2030	51



3.2.6	Conclusion of this test case	51
3.3	Renovation option for the test case 6	52
3.3.1	Current situation	52
3.3.2	Description of the renovation options	54
3.3.3	Water inflow for the next decades	55
3.3.4	Performance indicators over the concession period	57
3.3.5	Electricity market price in 2030	62
3.3.6	Conclusion of this test case	64
4	CONCLUSIONS	65
5	OUTLOOK AND NEXT STEPS	67
6	NATIONAL AND INTERNATIONAL COOPERATION	68
7	PUBLICATIONS	69
8	REFERENCES	70
9	APPENDICES	72
9.1	Validation for the test case 1	72
9.2	Validation for the test case 2	73
9.3	Validation for the test case 3	74
9.4	Validation for the test case 4	76
9.5	Validation for the test case 5	78



Abbreviations

BEP	Best Efficiency Point
GVO	Guide vane opening
LMH	Laboratory for Hydraulic Machines
MILP	Mixed Integer Linear Program
SFOE	Swiss Federal Office of Energy
SHAMA	Swiss Hydro Asset Modernization Assessment



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.

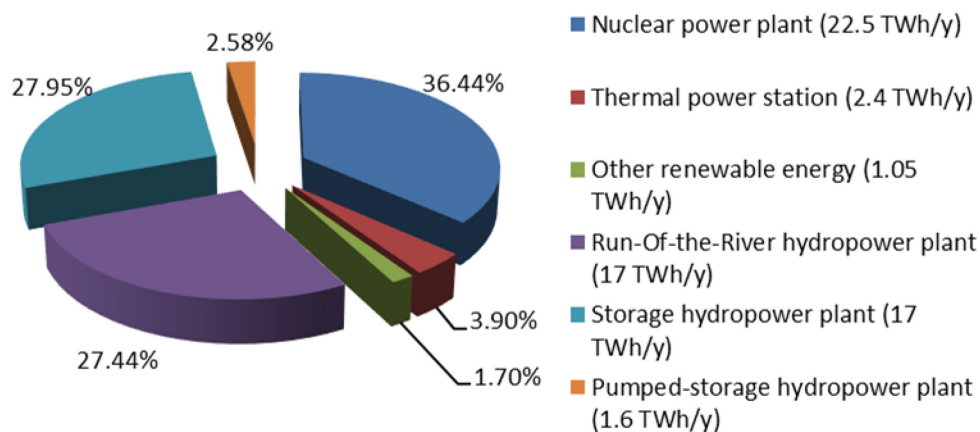


Figure 1: Electricity Generation Mix in Switzerland [2]

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*.

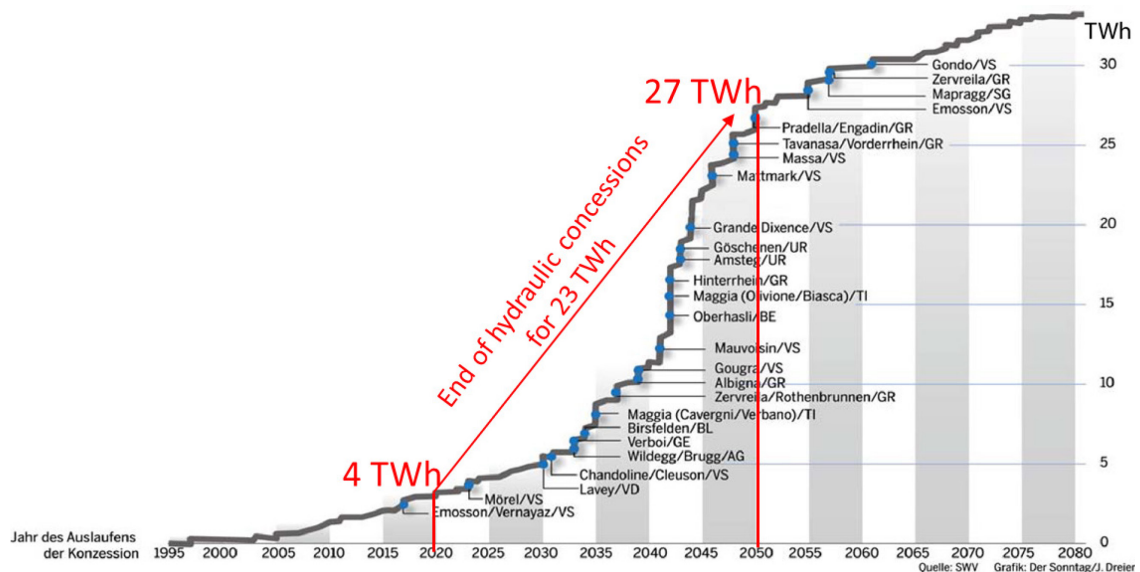


Figure 2: End of hydraulic concessions until 2080 (cumulative curve of annual productions).

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).

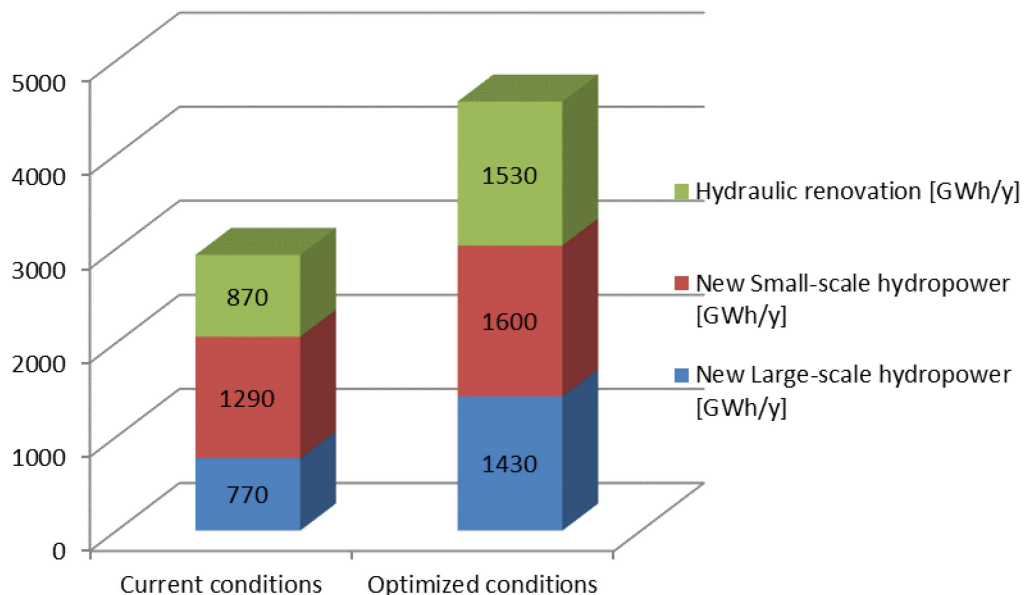


Figure 3: Estimated additional hydroelectric potential in 2050 [17]



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 is being developed by EPFL. However, the hydropower plant renovation is a long-term investment which economic performances are considerably influenced by the various political, economic and environmental factors that may evolve significantly in the coming decades. Therefore, the **Swiss Hydro Asset Modernization Assessment project** (SHAMA) aims at studying the impact of the political, economic and environmental contexts on the best technical solutions for hydropower plant renovation resulting from a systematic assessment process using the RENOVHydro Library. The various Swiss and European political strategies, the evolution of electricity price, climatic changes and environmental constraints are factors that have a direct impact on return on investment of the hydropower renovation.

1.2 Purpose of the project

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. However, this new SIMSEN library does not address the significant evolution of the political, economic and environmental contexts over the next decades. The SHAMA project proposes to assess the influence of these contexts in the decision-making process by considering scenarios describing the evolution of the electricity market price and hydrology time history for the next decades.

Hydrology models

Substantial changes in seasonal temperature and precipitation are expected in the future. Along with these changes in mean temperature and precipitation, the nature of extreme events is also expected to change. The assessment indicates more frequent, intense and longer-lasting summer warm spells and heat waves, while the number of cold winter days and nights is expected to decrease. In addition, a shift from solid (snow) to liquid (rain) precipitation is expected while glacier volume and related outflow are reducing. These changes will impact on the hydropower plant hydrology while new environmental constraints have to be taken into account.

Electricity market models

Originally, the return on investment of hydropower plants was mainly based on the total energy production and peak power capability while tacking advantages of intraday electricity price fluctuations. However, the recent increase of contribution of the New Renewable Energies in the power network modified considerably the electricity market in Europe leading to a situation of over electricity generation capability and currently low electricity price. Moreover, the intermittent nature of New Renewable Energies has considerably increased the need for ancillary services such as primary, secondary and



tertiary control. As consequences, the revenue sources of hydropower plants have significantly changed in the last five years. Moreover, several economic factors will influence the electricity market and therefore the return on investment of the pre-selected renovation solutions:

- Energy and climate policy of Switzerland and the European Union: The European 2020 energy goals are 20% reduction in CO₂ emissions compared to 1990 levels, 20% of the energy, on the basis of consumption, coming from renewables and a 20% increase in energy efficiency. This policy influences the economic attractiveness of renewable energy.
- Population and economic growth: According the International Energy Agency, World electricity demand will go up 85% by 2035. Switzerland should increase its electricity production to minimize its dependence on imports.
- Development of the renewable energy: The stochastic nature of the renewable energy production directly impacts the energy balance between generation and consumption. It has to be ensured the electrical grid has sufficient hydraulic reserve capacity, as well as primary and secondary control capabilities.
- Primary energy prices: The current decline in coal prices makes hydraulic electricity production less attractive. Investments in hydroelectric plant renewal decreases.
- Opening of the energy market.

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

The SHAMA Project addresses the renovation of an existing hydro power plant using the RENOVHydro Library and proposes to assess the influence of the electricity market price and hydrology time history for the next decades in the decision-making process.

First, probabilistic projections for the hydrology and the market price time history will be developed and applied to different watersheds and different types of hydraulic power plant. Then, the return on investment of the renovation option will be determined for the next decades with the computation of the internal rate of return. With this additional information, a renovation option that currently seems profitable may not be profitable in the second part of the century.

Finally, this systematic approach objectively compares the different renovation options proposed by the power utilities and determine their interest over the entire duration of the concession. The methodology implemented in this project is particularly interesting with relatively low electricity prices and increasingly alarming global warming.



2 Procedures and methodology

The SHAMA Project addresses the renovation of an existing hydro power plant using the RENOVHydro Library considering realistic time histories for the hydrology and market prices. In this chapter the methodology developed in the RENOVHydro project to compare different renovation options with a systematic approach is described in the section 2.1. The general procedure to define the evolution of the hydrology time history and the electricity market price time history over the next decades are described in the sections 2.2 and 2.3, respectively.

2.1 Methodology to select the best renovation options

The RENOVHydro project is dedicated to the renovation of an existing hydroelectric power plant and an independent assessment of a high number of civil and electromechanical potential modifications using a unique methodology. Thus, energy and economic indicators such as annual energy generation, annual amount of turbinized/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 4 and the workflow of the RENOVHydro project is described in Figure 10.

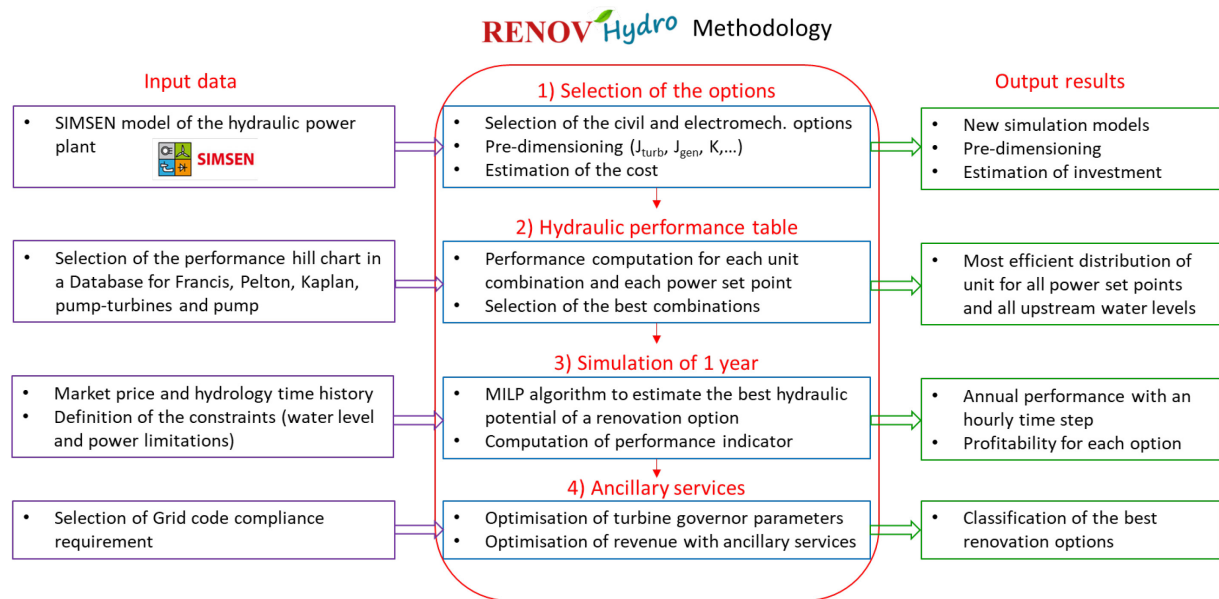


Figure 4 Methodology of the RENOVHydro project.

2.1.1 Selection of the options

This first step focuses on the importation of the SIMSEN model of the original hydraulic power plant and on the selection of civil and electromechanical engineering renovation options. The SIMSEN simulation software enables to model an entire power plant including hydraulic, mechanical and electrical system and their related control systems [13, 16, 18]. 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 bivariate functions based on Hermite polynomials [9].



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

An example of hill chart is illustrated in Figure 5. This performance hill chart selected in the database is compared with experimental measurement on a reduced scale model of a Francis turbine.

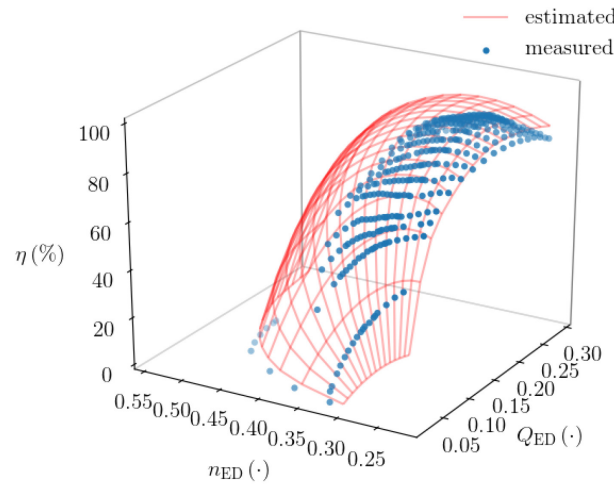


Figure 5 Performance hill chart from the database versus experimental measurement on reduced scale model of a Francis turbine.

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. 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.

2.1.2 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, 10, 15, 22, 23] 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 [12]. The maximum error found on more than 50 test cases was a maximum of 10 percent.

2.1.3 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.

2.1.4 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. 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 6 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 18 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.

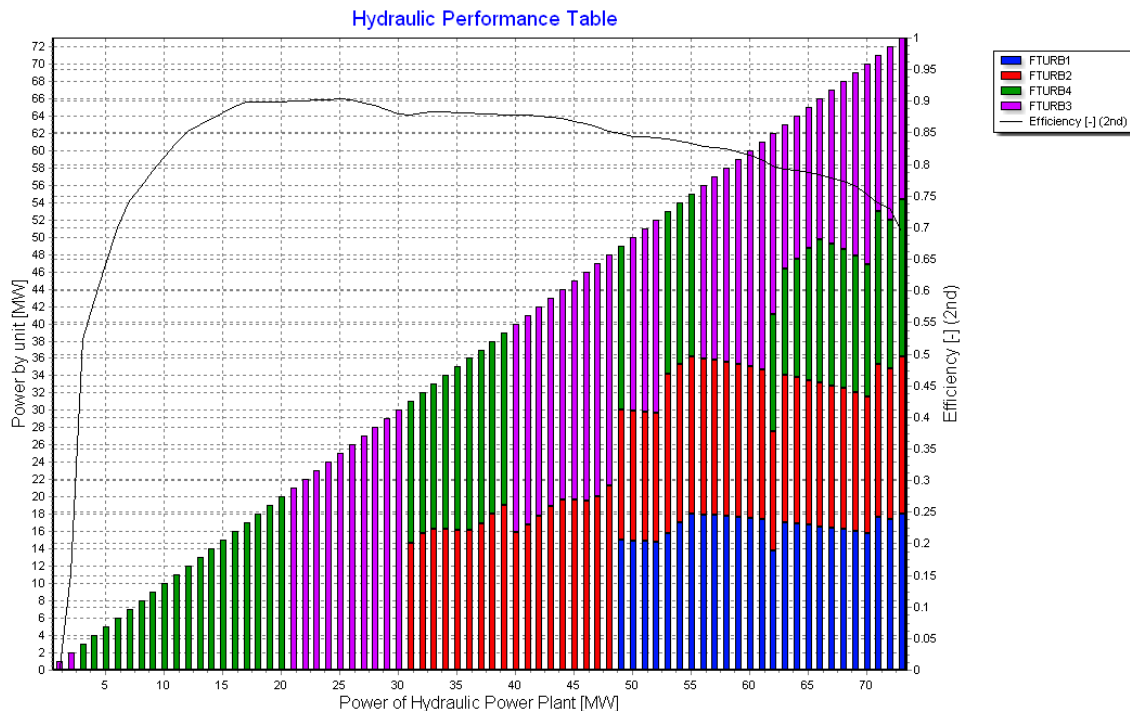


Figure 6 Hydraulic performance table for a given upstream water level and a hydraulic power plant with 4 Francis turbines, which provides the optimal distribution of power over the 4 units for a given total power set point and a given gross head.

2.1.5 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. Different scenarios will be considered estimating the impact of global warming on the temperatures and precipitations or estimating the impact of the politic decisions and the economy evolution on the electricity market. More information about these different scenarios are described in Sections 2.2 and 2.3.
- 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 turbinéd/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.



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: $\max(C^T x)$ 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.

2.1.6 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. 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 [19]. 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 7. 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.

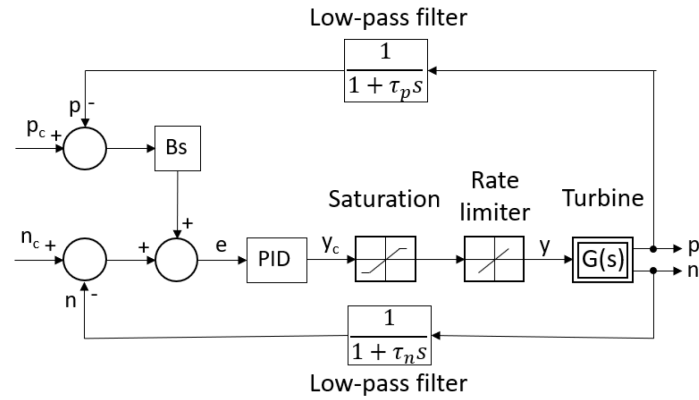


Figure 7 SIMSEN model of the control system.

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

The block diagram of the PID series used is presented in Figure 8, where K is the proportional gain, T_i is the integral time constant, T_d is the derivative time constant and m is the filter of the derivative term, range between 5 and 10.

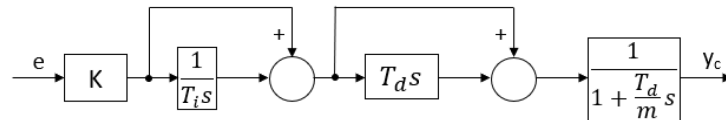
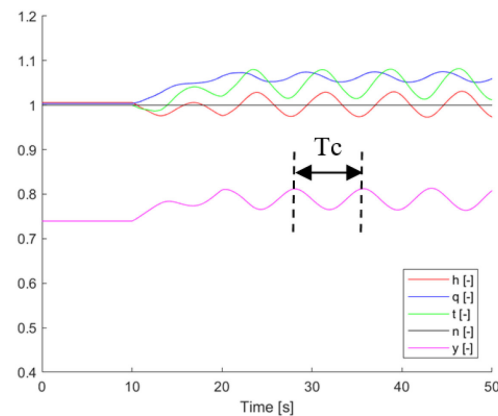
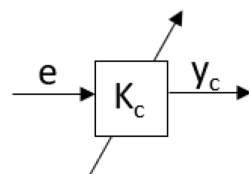


Figure 8 Block diagram of the PID controller in SIMSEN software.

The methodology used in the RENOVHydro library to determine the value of K , T_i and T_d is based on the Ziegler-Nichols method [14]. This method is divided in two different steps:

- The integral time constant T_i and the derivative time constant T_d are set to zero. The proportional gain K_c is then increased until it reaches the limit of stability, see Figure 9.



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

Figure 9 First step of the Ziegler-Nichols method: Limit of stability.



According to the proportional gain obtained in the first step K_c and the oscillation period T_c , the K , T_i , and T_d 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 to determine the PID parameters was applied and validated to 40 different Francis turbines with specific speeds N_q ranging between 20 and 130. The main objective was to validate the test for primary control capability defined by Swissgrid. According to the layout dimension defined in Landry et al. [14], 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 [22]: $Hadley = \frac{T_m}{T_w} = [2.35 - 9.36]$
- Wave reflection time: $T_r = \frac{2L_{penstock}}{a_{penstock}} = [0.15 - 2.5]$

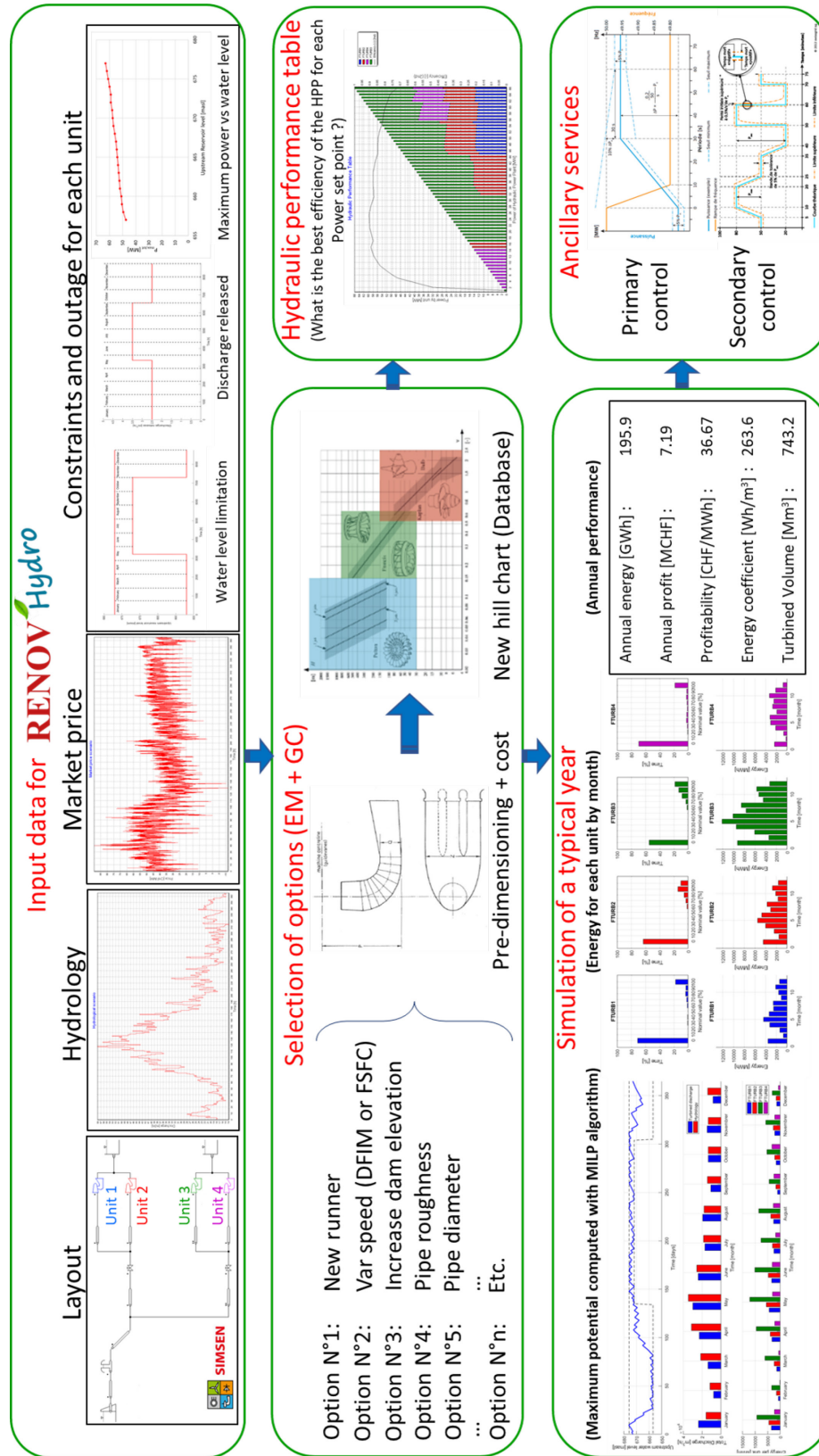


Figure 10 Workflow of the RENOVHydro project.



2.2 Hydrology scenarios building

The CH2011 projections [24] focus on changes in temperature and precipitation. Probabilistic seasonal mean changes are provided using a multi-model approach for three representative regions of Switzerland (northeastern Switzerland, western Switzerland and Switzerland south of the Alps). The CH2011 projections assumes two non-intervention emission scenarios (A2 and A1B) that anticipate increases in emission and one climate stabilization scenario (RCP3PD) that supposes emissions are cut by about 50% by 2050, see Figure 11:

- **Scenario 1 (RCP3PD)** illustrates an emission scenario that stabilizes the atmospheric CO₂ equivalent concentration near 450 ppm by the end of the century. This scenario likely prevents global warming of more than two degrees Celsius since the pre-industrial period.
- **Scenario 2 (A1B)** is characterized by a balance across fossil-intensive and no fossil energy sources. This scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies.
- **Scenario 3 (A2)** describes a very heterogeneous world. The population increases continuously. The economic development is regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other emission scenarios.

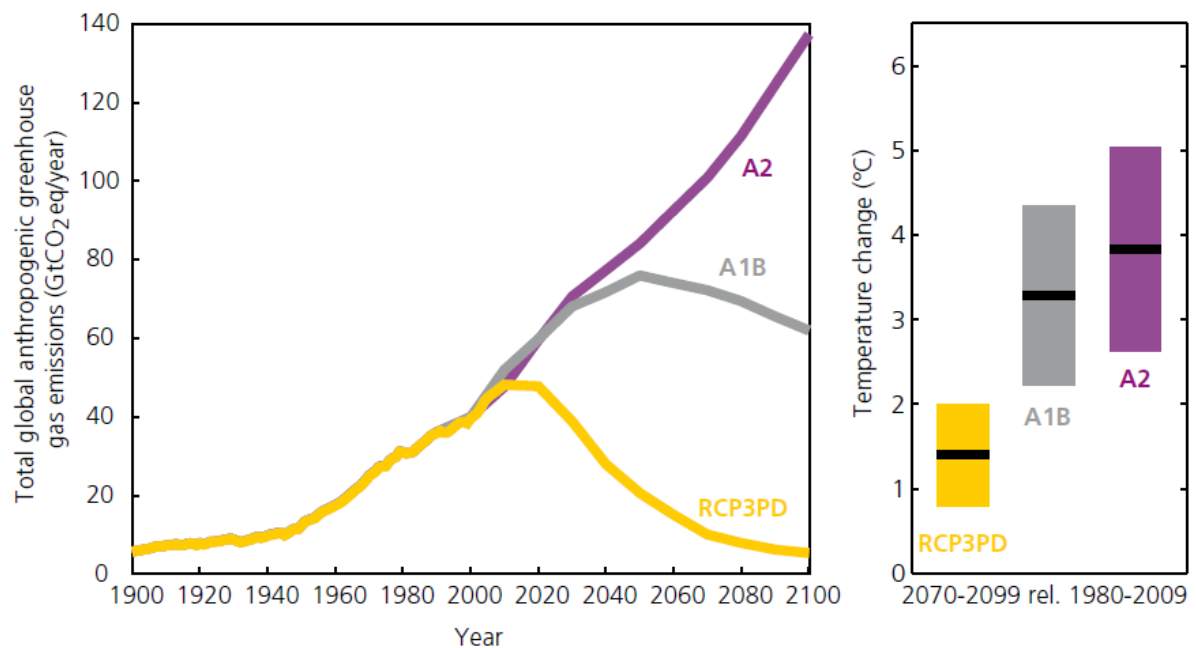


Figure 11 Comparison of the total global anthropogenic greenhouse gas emissions for hydrology scenarios [24]

These three scenarios were used as reference and were adapted to the test case watershed to obtain a realistic hydrology time history for the next decades. To apply these scenarios, the CH2011 program provides a dataset for regional scenarios at daily resolution:

- for 3 regions (North-East, South, West),
- for 3 scenarios periods (2020-2049, 2045-2074, 2070-2099)
- for 3 scenarios (A2, A1B, RCP3PD). The presented scenarios possess regional resolution, neglecting any spatial variability of the climate change signal within a region.



This dataset provides a factor to determine the expected changes in temperature and precipitation. The procedure is the following:

- **For the temperature**, the expected future temperature for a selected scenario and for a selected period is obtained by adding the temperature changes provided in the dataset for the corresponding days of the year to the observed time series temperature in the reference period.
- **For the precipitation**, the expected future precipitation for the scenario period is obtained by multiplying the precipitation changes provided in the data set for the corresponding days of the year by the observed time series of precipitation in the reference period.

Finally, the methodology to build the hydrology scenarios is the following:

- First, reference hydrology data provided by the Power utilities is studied to determine the trend of seasonal temperature and precipitation assessment over the previous years for the test case watershed.
- A typical year is selected, without heat waves or heavy precipitation, and form the basis for the projection of different scenarios.
- Precipitation and mean temperature change projections is determined with the CH2011 projections until 2100. These projections are adapted to the test case watershed and combined with the typical year selected.

With these information, annual hydrology scenarios with hourly time step are deduced for each scenario. Hydrographs are generated to describe a realistic hydrology time history for the 3 scenarios periods taking into account the trend related to its specific scenario. By considering the series of hydrographs, it is possible to assess the impact of global warming on the performance assessment and the ancillary services capability of the hydropower plant and the corresponding best renovation solution. The detailed methodology used for the hydrology scenarios building is illustrated in Figure 12.

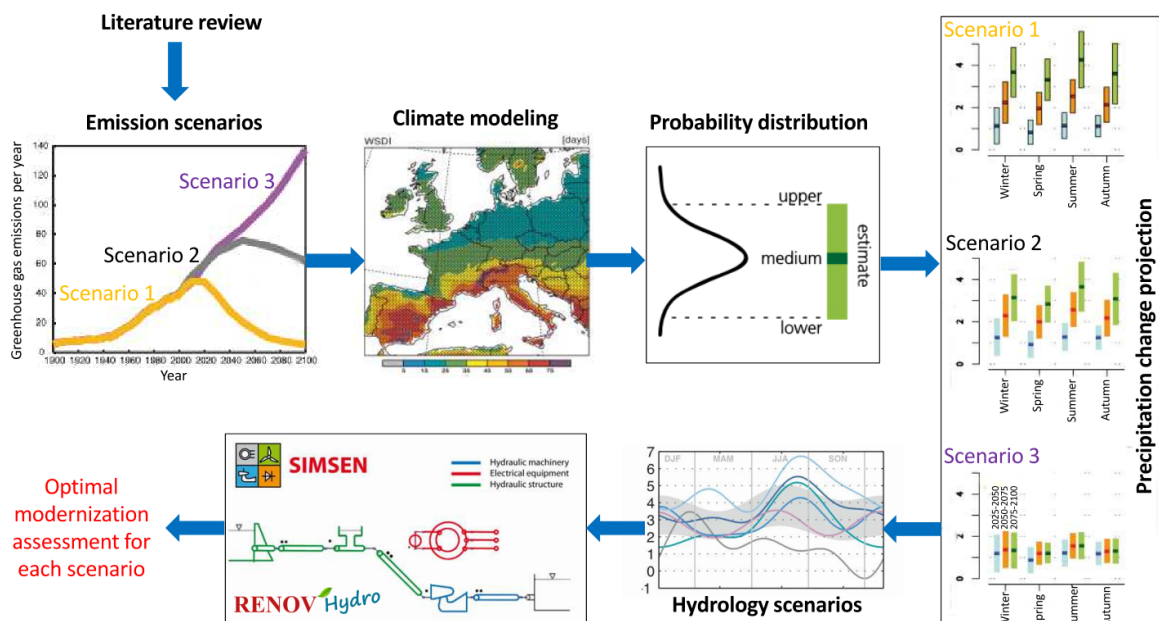


Figure 12 Methodology for hydrology scenarios building



2.3 Electricity market scenarios building

In the last years, low carbon and fuel prices induced a general decrease of electricity prices in Europe and therefore the hydro power plants return on investment decreased. As hydropower covers about 60% of electricity generation in Switzerland, the reduced return on investment over the past years has led to a debate on the financial support for the Swiss hydro power plants [3]. For the two types of hydraulic power plant, the electricity market price variation has different impacts [8, 25]:

- **The run-of-river power plants** are running continuously and have to recover their costs given the average market price. Their return on investment strongly depends on the development of the EU generation mix, the global fuel markets and the European Union Emissions Trading System (ETS). As Switzerland has no influence on this development, Swiss hydro power plant has to adapt to whatever development will materialize.
- **The storage power plants** are focusing on high price peak load hours and thus have to recover their costs in fewer hours during the year. The participation on balancing markets could provide a significant revenue increase and thereby partially mitigate the overall decline in prices.

For the future, Schlecht and Weigt [21] showed that given the expected European capacity extension plans for renewables and conventional generation, the price pattern will be altered significantly. The emergence of large-scale solar generation will lead to significant price dumps during daytime and price spikes in morning and evening hours. However, the existing and projected conventional capacities will lead to a rather flat price curve during the transition phase that can likely prevail for up to two decades until renewables have a much higher market share.

Currently, the different models presented in the literature showed that the market price prospects for Swiss hydro power plants until 2030 are mixed. Within the next five years, the existing European plant capacities are likely to keep prices on comparable levels as today. **Afterwards the price development becomes less predictable and strongly depends on the development of carbon and fuel prices.** The scenarios proposed by Schillinger et al. [20] span a range of low and high price pathways until 2030, see Figure 13. The scenarios with high renewable deployment (RES+) and low carbon and fuel price assumptions describe lower price end. Therefore, the high price scenarios describe high carbon and fuel price assumptions (CO2++Fuel++). However, all scenarios have a modest price level in 2020 meaning that the current low prices are expected to remain for some more years.

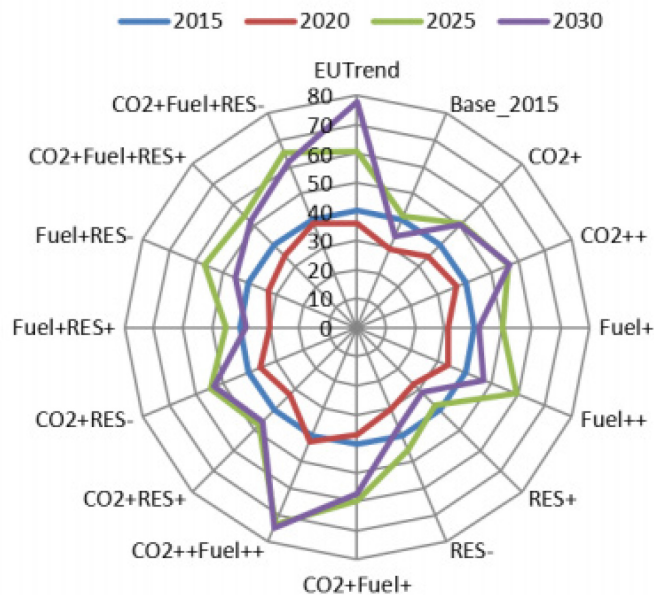


Figure 13 Future spot market prices [€/MWh] by scenario [20]

For the SHAMA project, the power utilities provided 3 different electricity market scenarios for the next decade (up to 2030) based on Schillinger et al. [20].

- **Scenario 1** describes a hardening moderate of the targets fixed for energy and environmental policy. This scenario is defined by a high hydrocarbon consumption and electricity prices will be high.
- **Scenario 2** assumes that the Swiss society will experience a significant change in its values. Public opinion and political climate actively support the improvement of energy efficiency and development of renewable energy.
- **Scenario 3** assumes the Swiss society will experience a fundamental change in values, with an open mind to renunciation. By 2050, 100% of the electricity supply on annual average will come from renewable energy sources. The price of the electricity will be low.

Finally, for each scenario, a realistic electricity market price time history with hourly time step is defined until 2030, see Figure 14. Afterwards, the electricity market becomes less predictable and strongly depends on the development of carbon and fuel prices. It becomes impossible to define realistic electricity market price evolution.

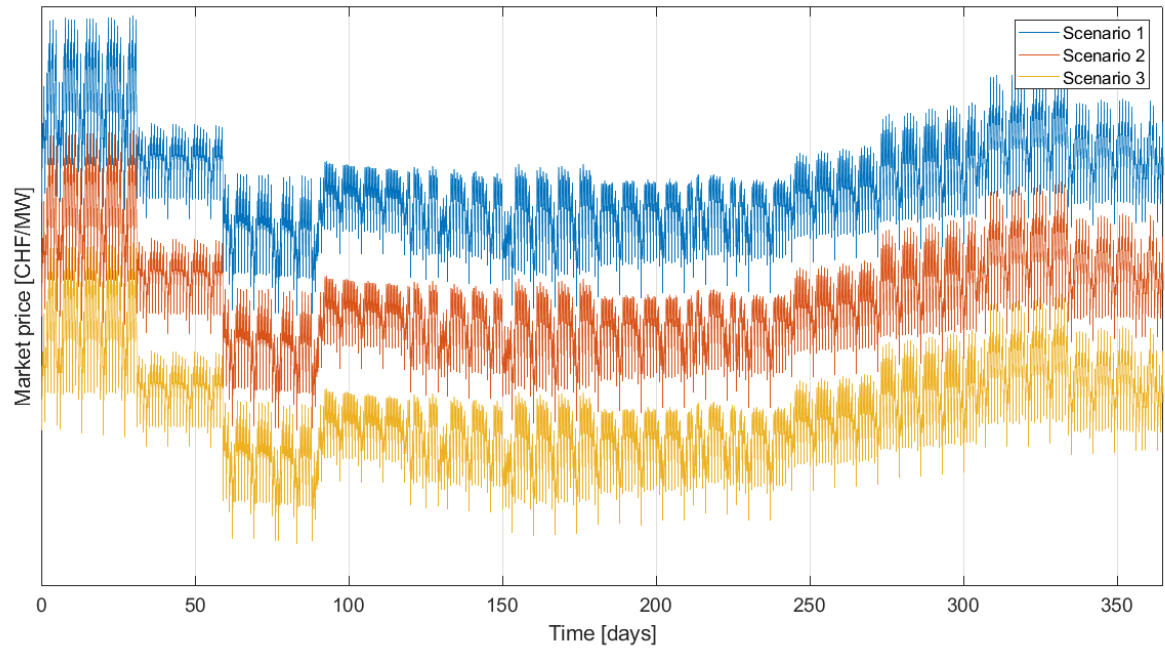


Figure 14 Electricity market price time history with hourly time step in 2030 for the 3 scenarios.



2.4 Test case modernization potential assessment

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, 6 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 section, after a description of each test case, a selection of the hydropower plant renovation options is proposed. The application of the methodology previously presented is applied in Chapter 3.

2.4.1 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 15. 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.

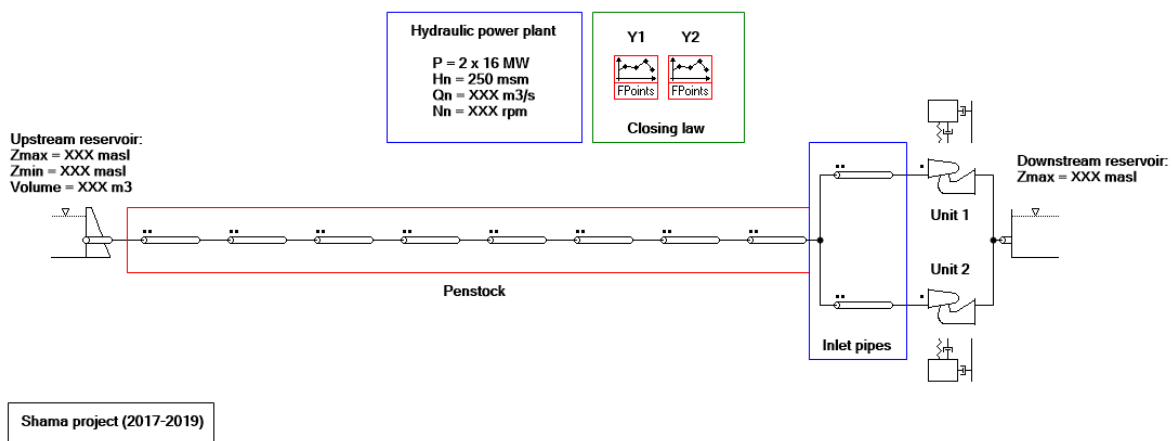


Figure 15 SIMSEN model of the test case 1.

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 3.1.

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 next chapter.



2.4.2 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 16. 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.

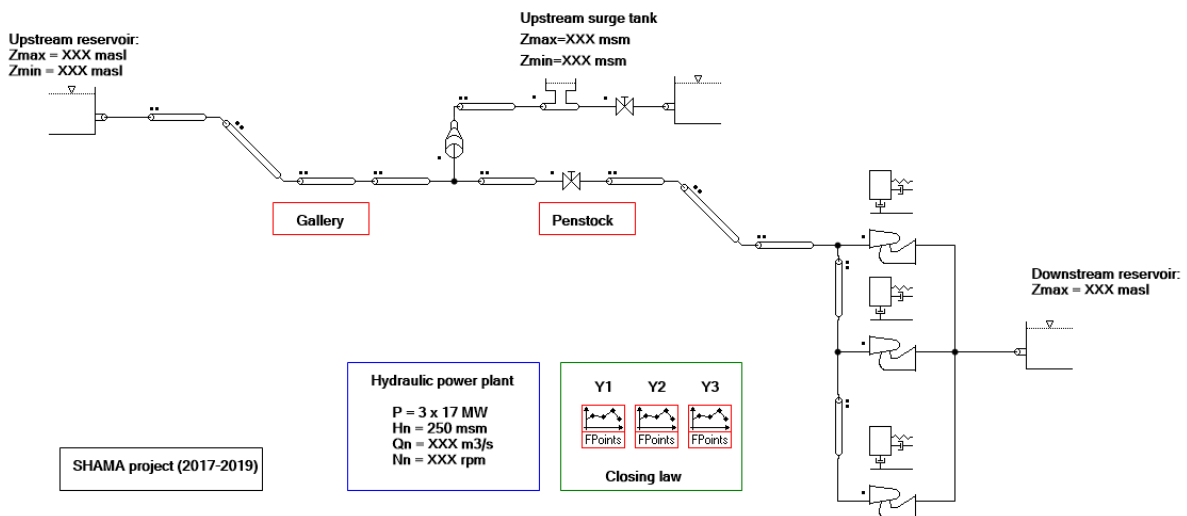


Figure 16 SIMSEN model of the test case 2.

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.



2.4.3 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 17. 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.

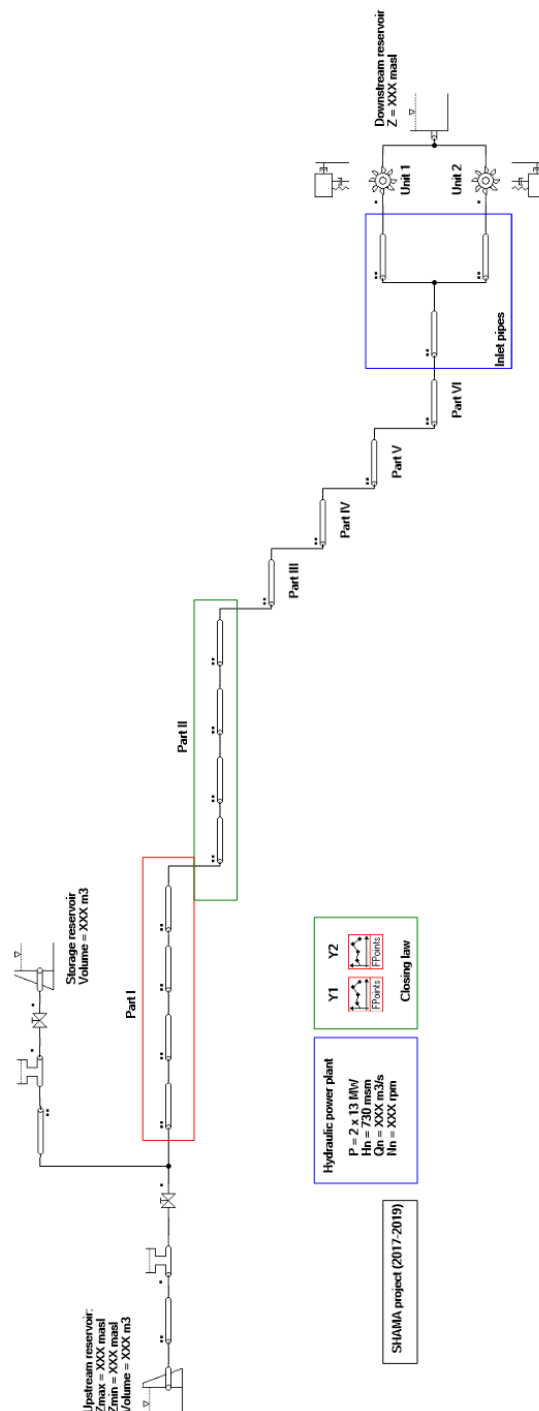


Figure 17 SIMSEN model of the test case 3.



2.4.4 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 18. 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.

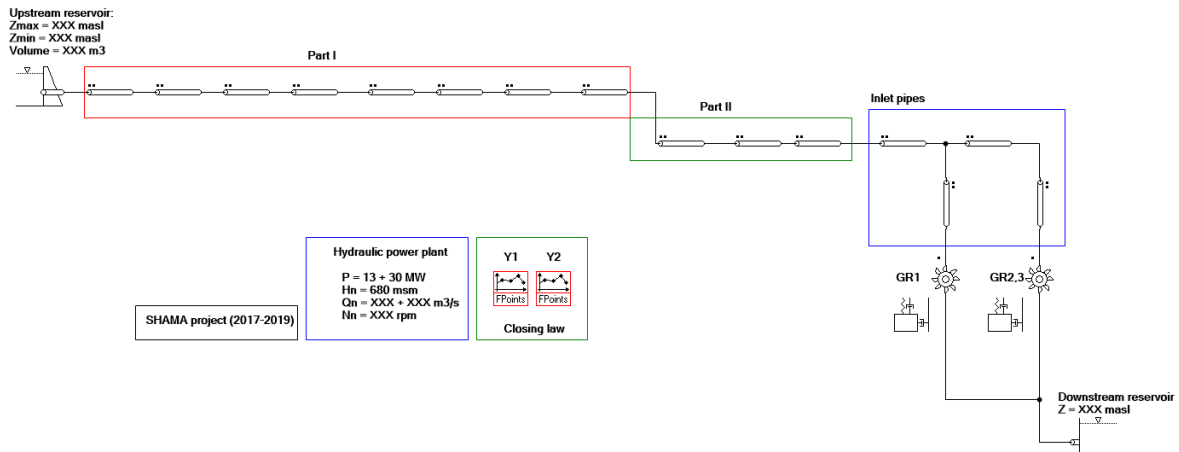


Figure 18 SIMSEN model of the test case 4.

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 3.2.

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 the next chapter.



2.4.5 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 19. 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.

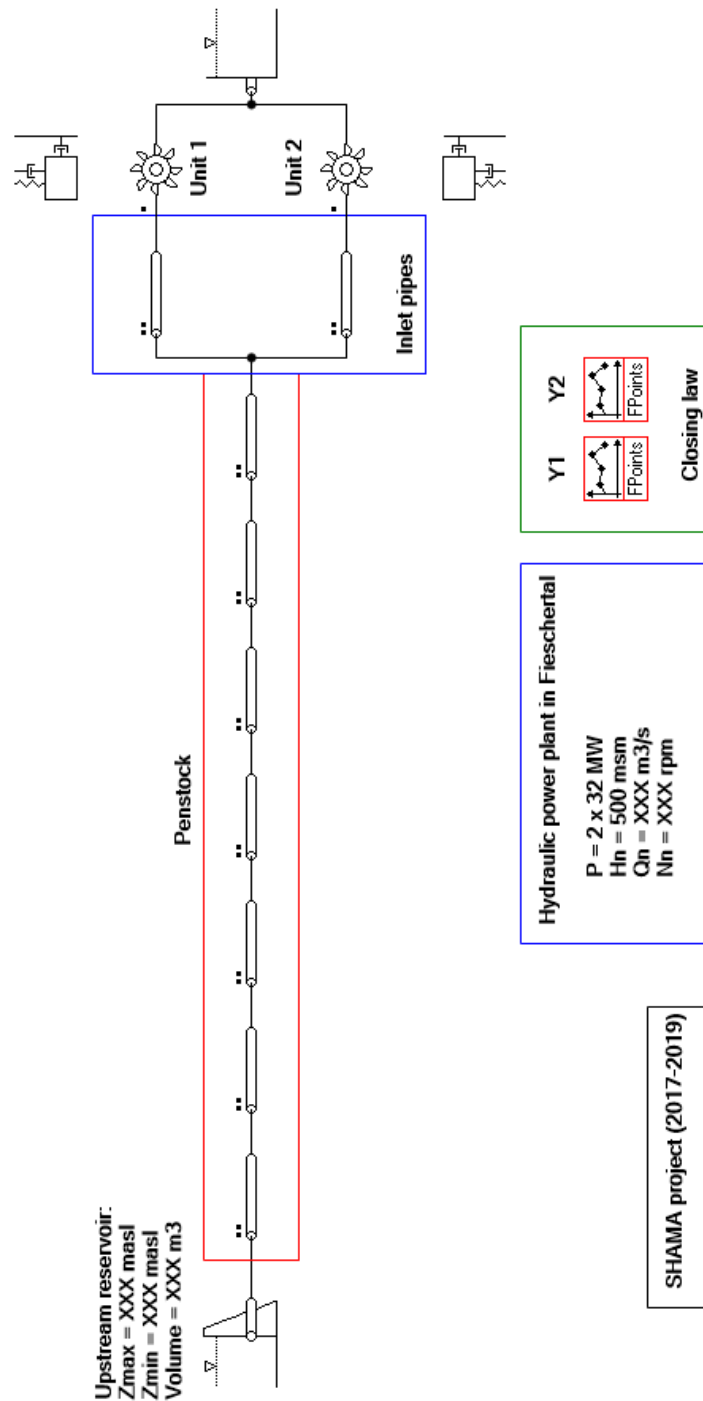


Figure 19 SIMSEN model of the test case 5.



2.4.6 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 [14].

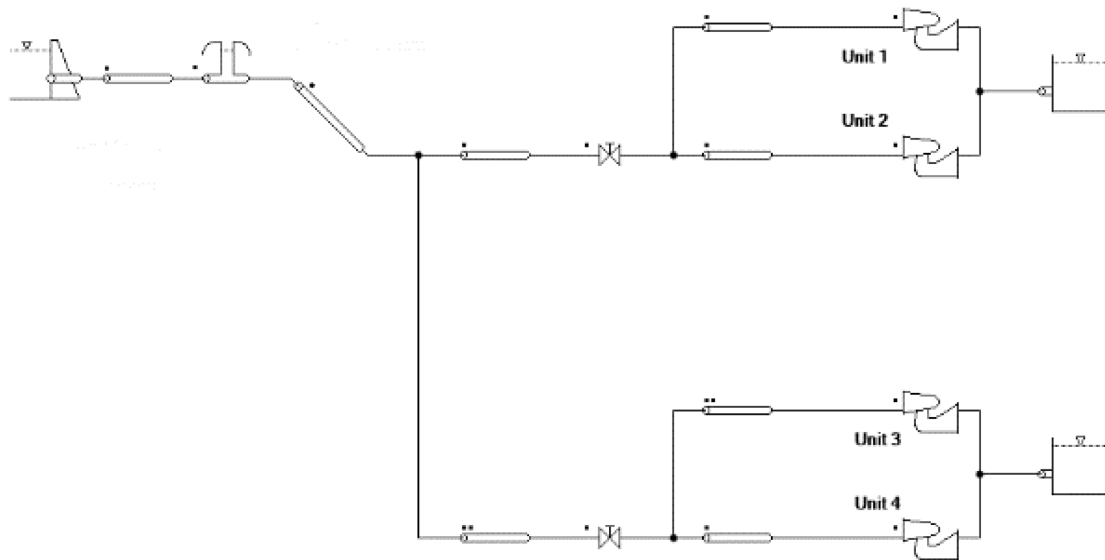


Figure 20 SIMSEN model of the test case 6

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 3.3.

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



3 Results and discussion

3.1 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 turbinized 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, **but is it still interesting if we consider the climate change over the coming decades?**

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. Then, the variation of the water inflow will be presented by considering the temperature and the precipitation variations until 2100. Finally, the performance indicators will be computed for the whole century to determine the return on investment of this renovation option.

3.1.1 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 21.

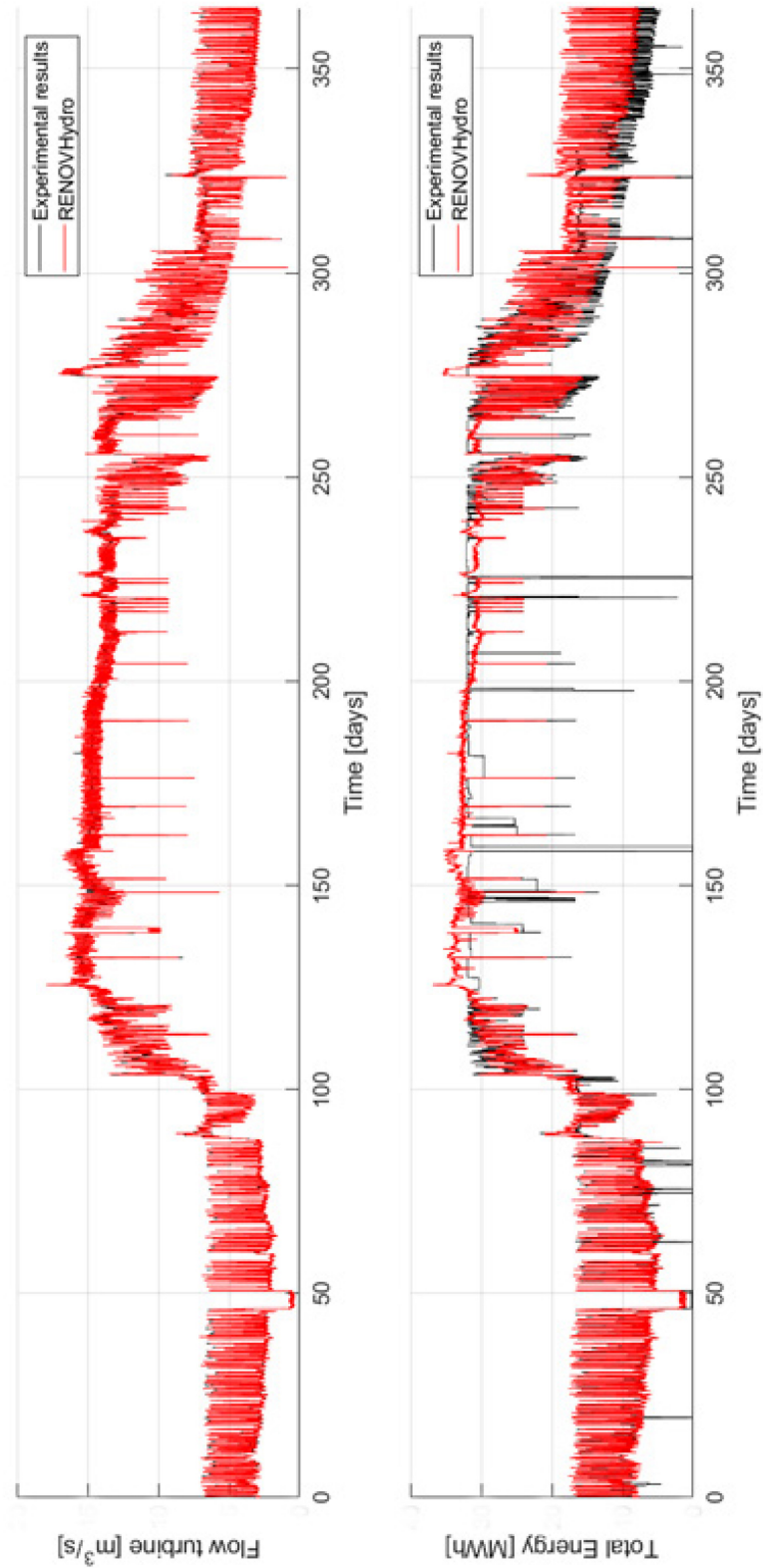


Figure 21 Turbined flow and energy production generated in 2017 (hourly time step). In black, the measurement provided by the power utility. In red, the numerical results with the RENOHydro library.



3.1.2 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: $L = 3'890 \text{ m}$
- Diameter of the pipe: $D = 1.8 \text{ m}$
- Steel cost: $\text{Cost} \approx 26 \text{ MCHF}$
- Installation cost: $\text{Cost} \approx 4.9 \text{ MCHF}$
- 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: $L = 910 \text{ m}$
- Diameter of the pipe: $D = 1.8 \rightarrow 1.65 \text{ m}$
- Steel cost: $\text{Cost} \approx 5.9 \text{ MCHF}$
- Installation cost: $\text{Cost} \approx 1.1 \text{ MCHF}$
- 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.

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 22. 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.

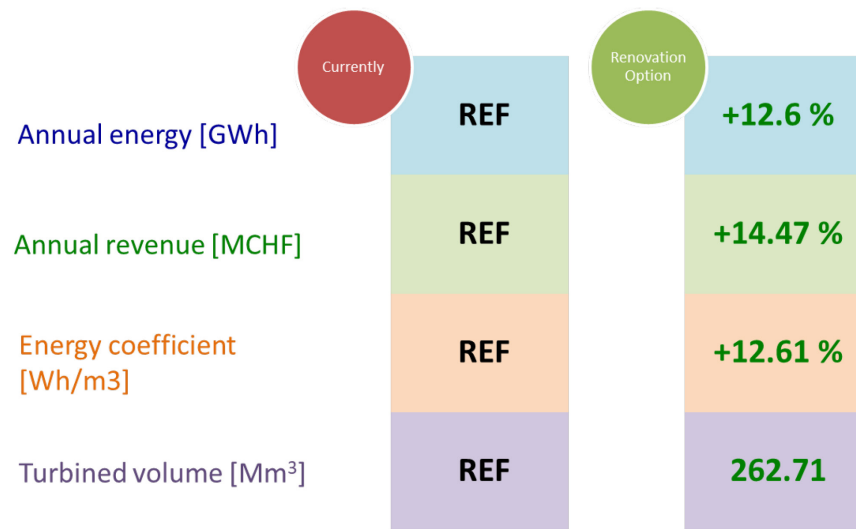


Figure 22 Comparison of the performance indicators between the current situation (Reference) and the renovation options.



3.1.3 Water inflow for the next decades

The water inflow for the next decades was obtained by the method described in Section 2.2. As reminder, the CH2011 projections assumes two non-intervention emission scenarios (A2 and A1B) that anticipate increases in emission and one climate stabilization scenario (RCP3PD) that supposes emissions are cut by about 50% by 2050.

The analysis of the evolution of the water inflow during the next decades indicates drier months between June and September, thus reducing the total amount of water that can be turbinéd throughout the year. This effect is very pronounced for the scenario A2. Finally, whatever the scenario, the water inflow between October and April remains stable throughout the century, see Figure 23.

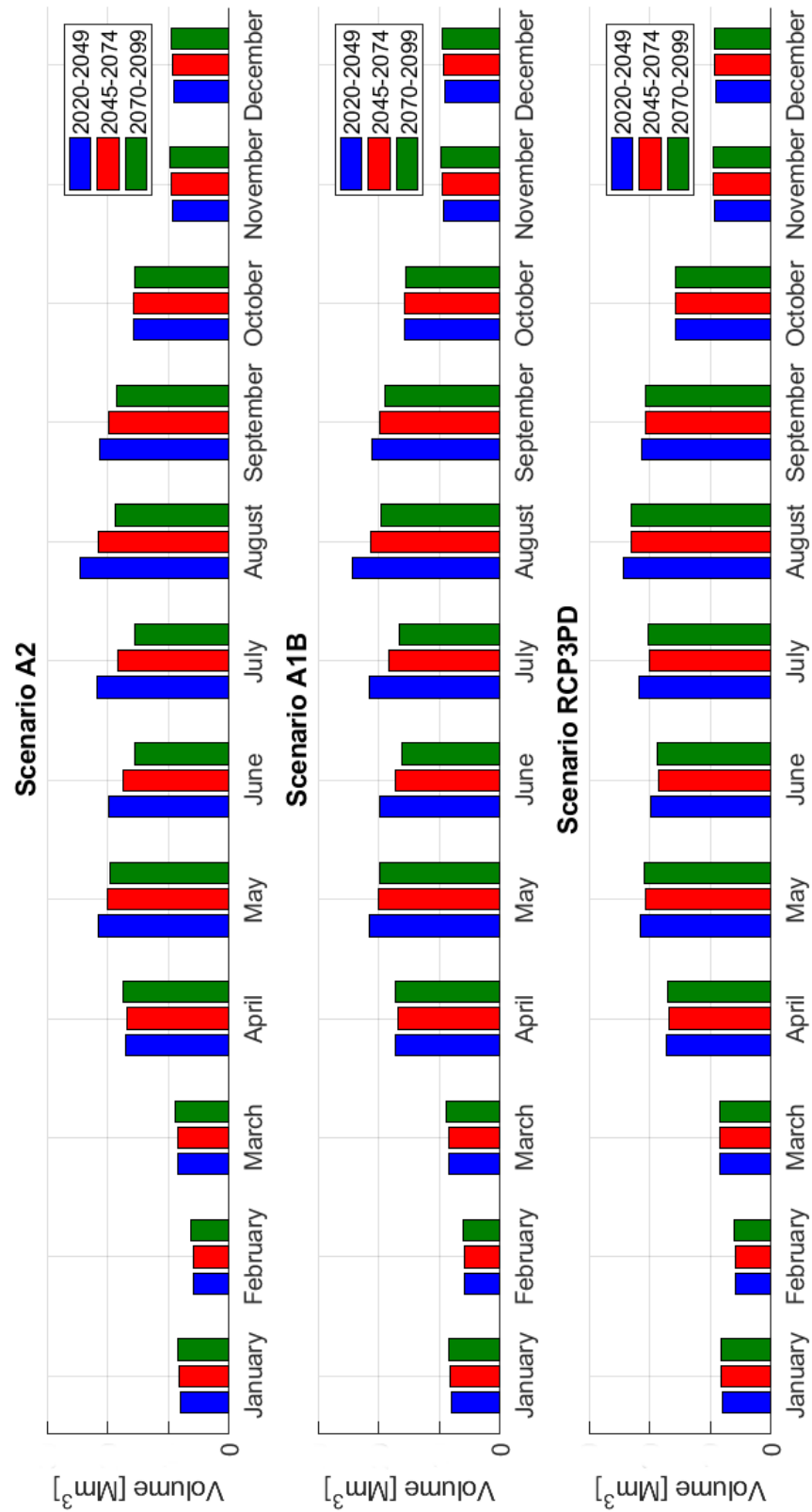


Figure 23 Variation of the water inflow for the next decades with a monthly time step.



3.1.4 Performance indicators over the concession period

The variation of the performance indicators over the concession period, using the new hydrology time history are described in Figure 25. The values are all expressed as a percentage and referenced to the current situation. Despite a sharp reduction in water inflows by the end of the century, the annual revenue is still higher than the current value, regardless of the hydrological scenario. Thus, this renovation option makes it possible to better exploit the energy available.

To determine if the project is profitable, the internal rate of return is computed to estimate the investment's rate of return, see Figure 24. Over an 80-year period, the annuity factor is equal to 3.31% if the interest rate is set at 5% and the inflation rate at 2%. In addition, the operating and maintenance costs rate for the electromechanical and civil equipment was set at 4% and 1.4% respectively. Thus, whatever the hydrological scenario, the internal rate of return is higher than 5% and this renovation option could be profitable over the concession period.

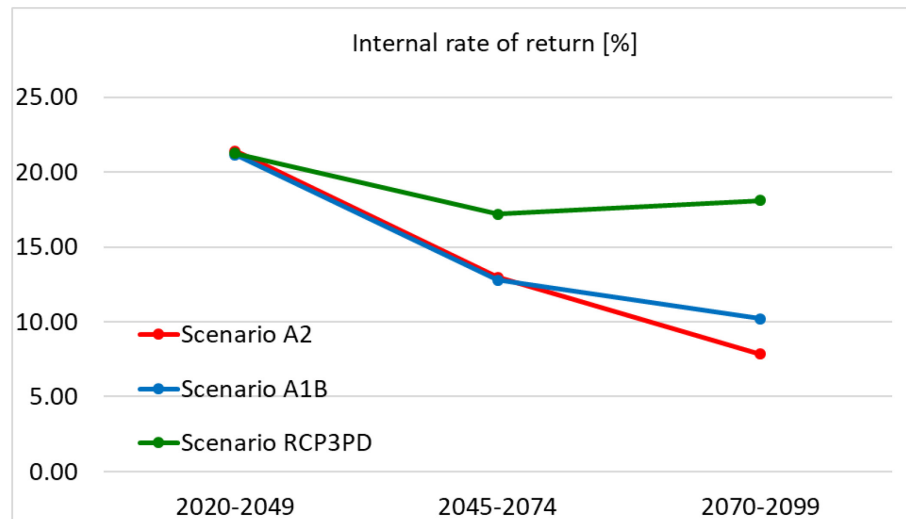


Figure 24 Evolution of the internal rate of return as function of the scenario.

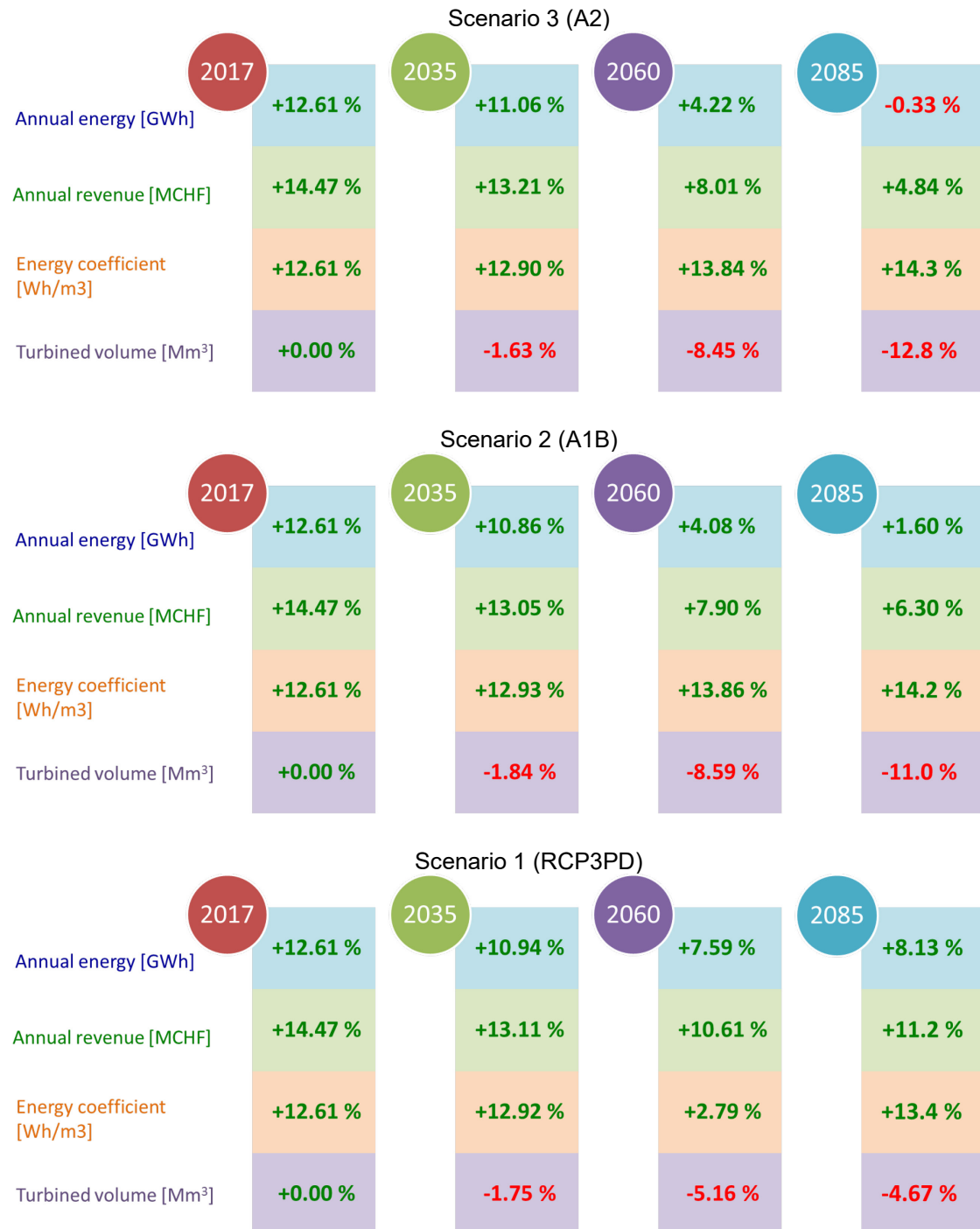


Figure 25 Performance indicators for the next decades.



3.1.5 Electricity market price in 2030

In general, hydro power plant has high capital costs but low operating costs while the level of costs depends on the specific site and additional factors such as national regulation [8]. Since electricity prices decreased in the past years due to an increasing share of renewable energies and low fuel and carbon prices, the return on investment of hydro power plant has decreased. However, the return on investment situation cannot be generalized since costs are highly heterogeneous [3, 20]. The 3 different electrical scenarios described in Section 2.3 are therefore applied to this renovation option, see Figure 26. As the impact of the hydrological scenarios is very low for the first period (2020-2049), the study was applied only for scenario A1B.

The evolution of the electricity market has a strong impact on the maximum annual revenue that can be provided by the hydraulic power plant. However, since the uncertainty in this electricity market is high and depends on future decision-making by European countries, it is difficult to define the return on investment of a project over the concession period. However, as the computation described in the previous section was performed with the current market price and as the current electricity prices in Europe is low, the value of the internal rate of return is low estimation. The trend in the coming decades would rather be to have more attractive electricity prices and therefore an even better return on investment of the renovation project.

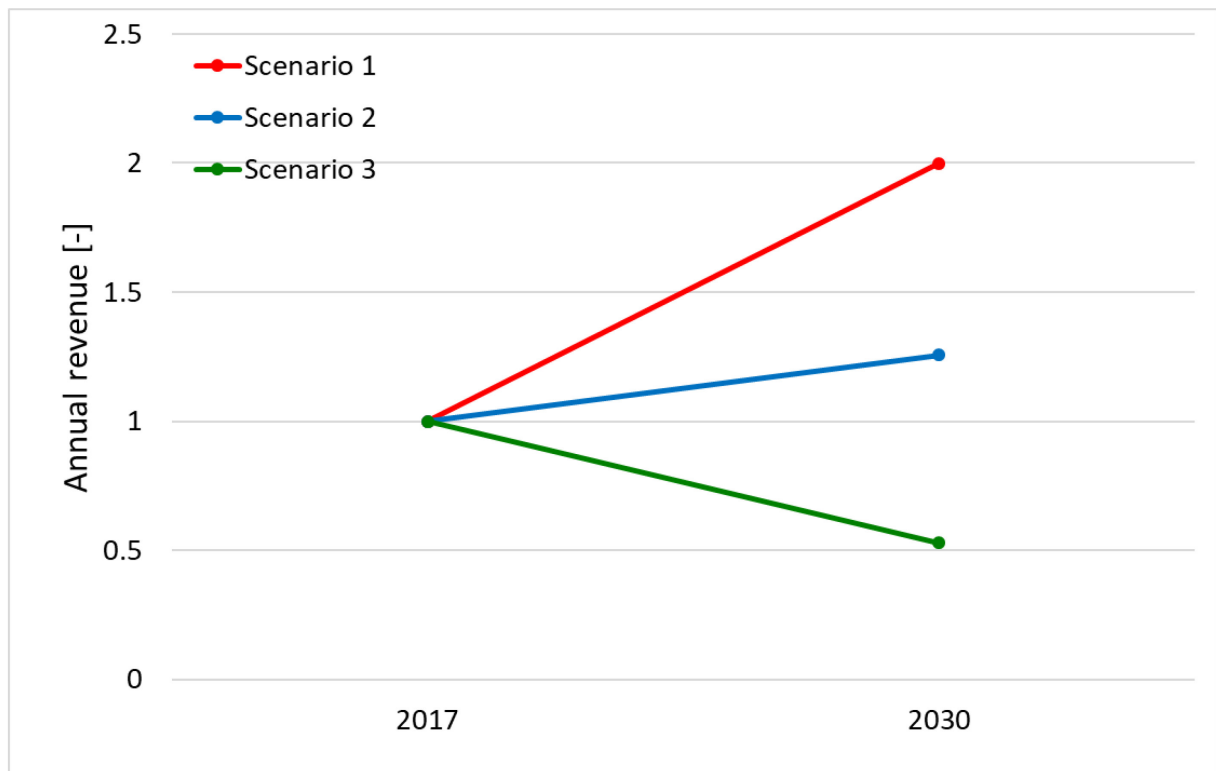


Figure 26 Variation of the annual revenue as function of the electrical scenario (the values are referenced to the annual revenue in 2017)



3.1.6 Conclusion of this test case

The SHAMA project made it possible to take climate change into account in the analysis of renovation option over the concession period. 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. In this particular test case, despite a sharp reduction in water inflows by the end of the century, the annual revenue is still higher than the current value, regardless of the hydrological scenario. Thus, whatever the hydrological scenario, the internal rate of return is higher than 5% and this renovation option could be profitable over the concession period. Finally, this estimation of the renovation return on investment is a low value given the current electricity prices in Europe.

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 serves to highlight the most interesting renovation options. Thus, the performance indicators described are not absolute values, but only aids in decision-making.



3.2 Renovation option for the test case 4

The most interesting renovation option is to increase the storage volume of the upstream reservoir, see Figure 27, 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. **But is it still interesting if we consider the climate change over the coming decades?**

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. Then, the variation of the water inflow will be presented by considering the temperature and the precipitation variations until 2100. Finally, the performance indicators will be computed for the whole century to determine the return on investment of this renovation option.



Figure 27 Current upstream reservoir.

3.2.1 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 28.

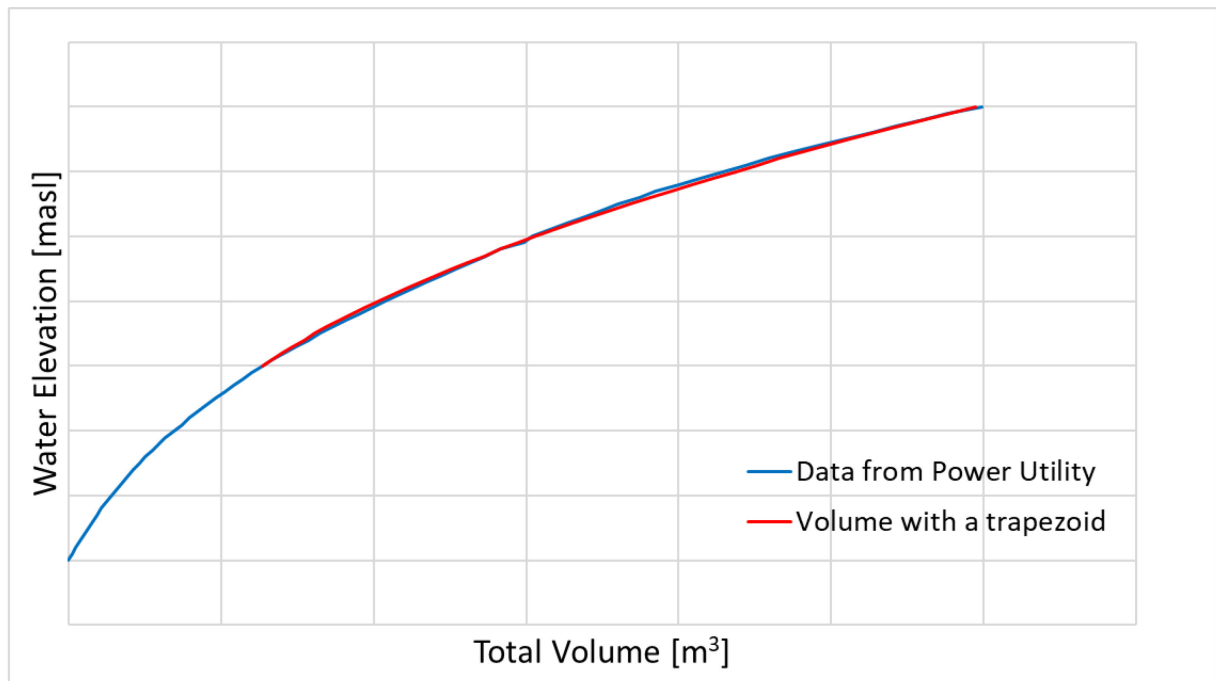


Figure 28 Current volume as function of the water elevation. The variation of the volume can be defined by a trapezoid.

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 29. The monthly total energy illustrated in Figure 30 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.

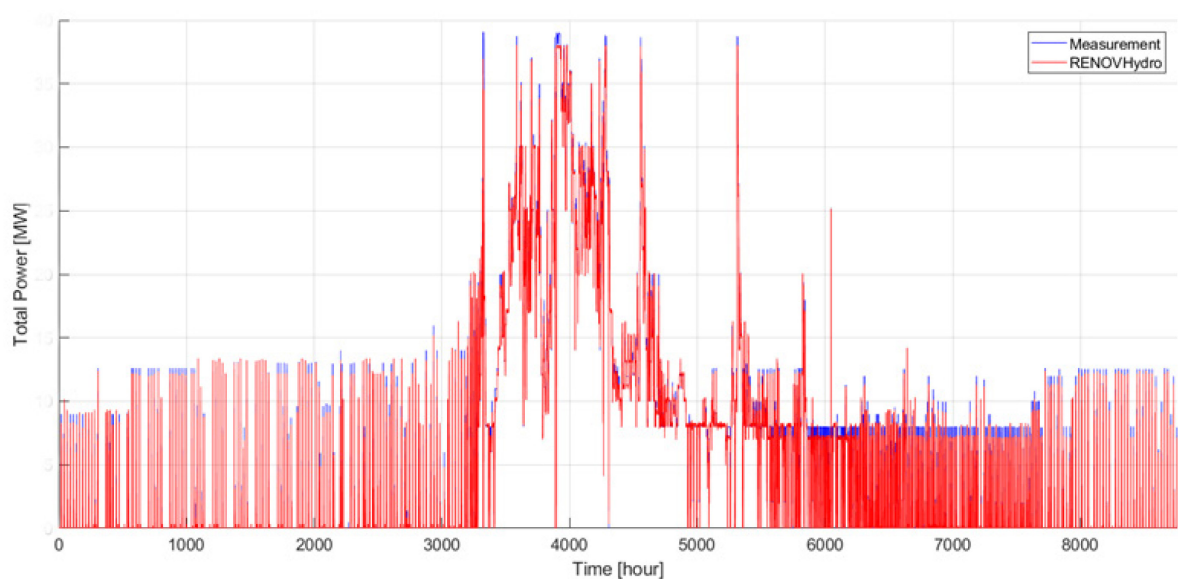


Figure 29 Energy production generated in 2017 (hourly time step). In blue, the measurement provided by the power utility. In red, the numerical results with the RENOvhydro library.

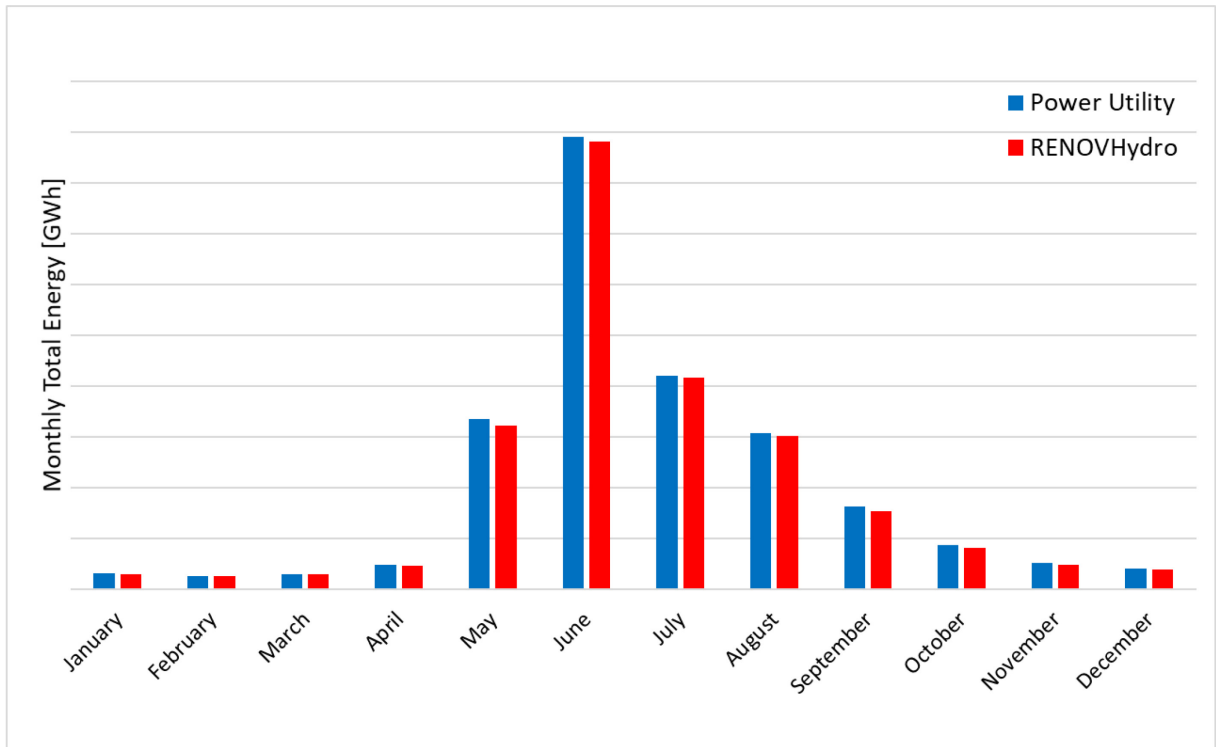


Figure 30 Comparison of the monthly total energy between the real data and numerical results with the RENOVHydro library.



3.2.2 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 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 **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**.

With this increase in the storage volume of the upstream reservoir, the turbined volume and the water inflow are still the same. However, the turbined volume can 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 31. 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 32. 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.

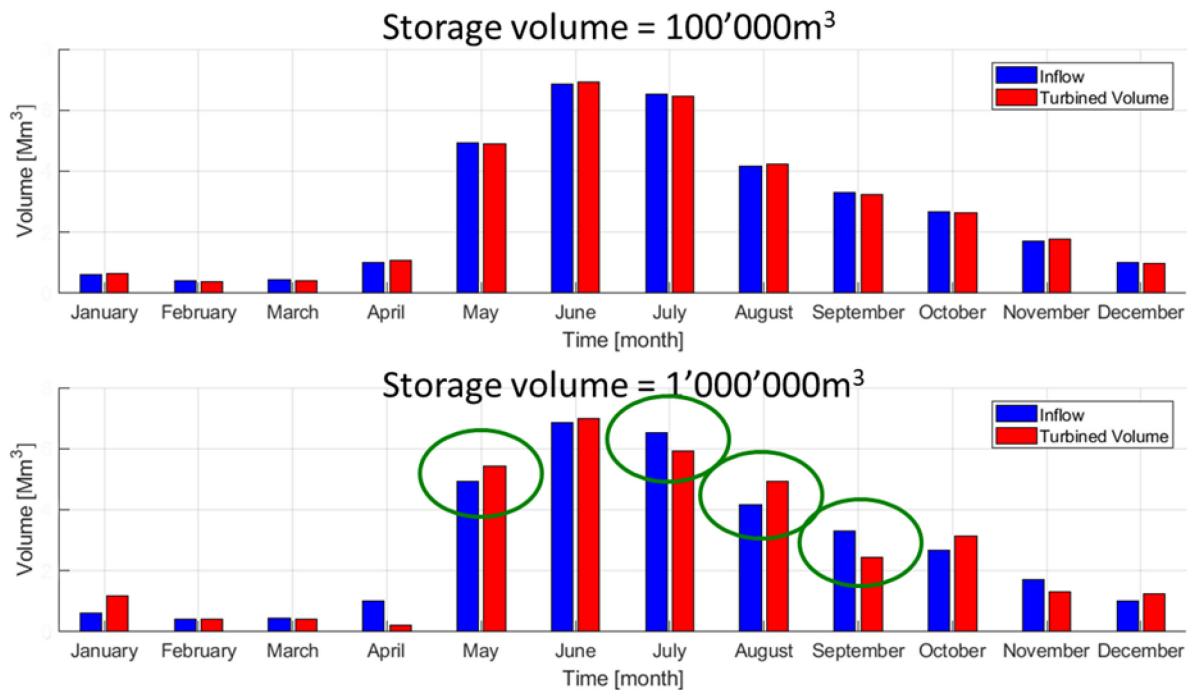


Figure 31 Comparison of the turbined volume and the inflow for the two different reservoirs. With the big reservoir, the turbined volume is no longer always equal to the volume of water inflow.

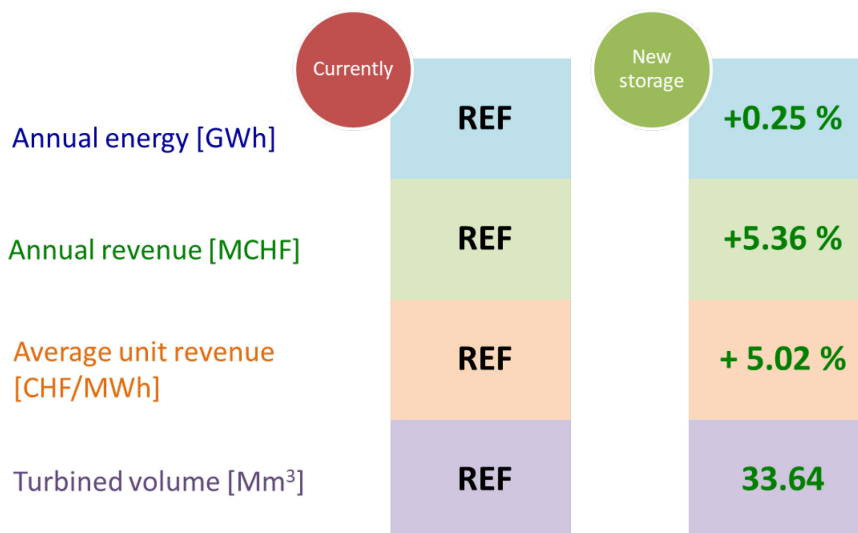


Figure 32 Comparison of the performance indicators between the current situation (Reference) and the renovation options.



3.2.3 Water inflow for the next decades

The watershed being complex, composed of glacier in the heart of the Alps, the Hydrique company was mandated by the power utility to have a more precise idea of the water inflow in the future, considering the temperature increased, the melting of snow and glaciers and the variation of the precipitation, see Figure 33.

The analysis of the evolution of the water inflow during the next decades indicates wetter months between April and May, resulting in a sharp increase of the turbinéd water. However, significantly drier months will follow between June and September, thus reducing the total amount of water that can be turbinéd throughout the year.

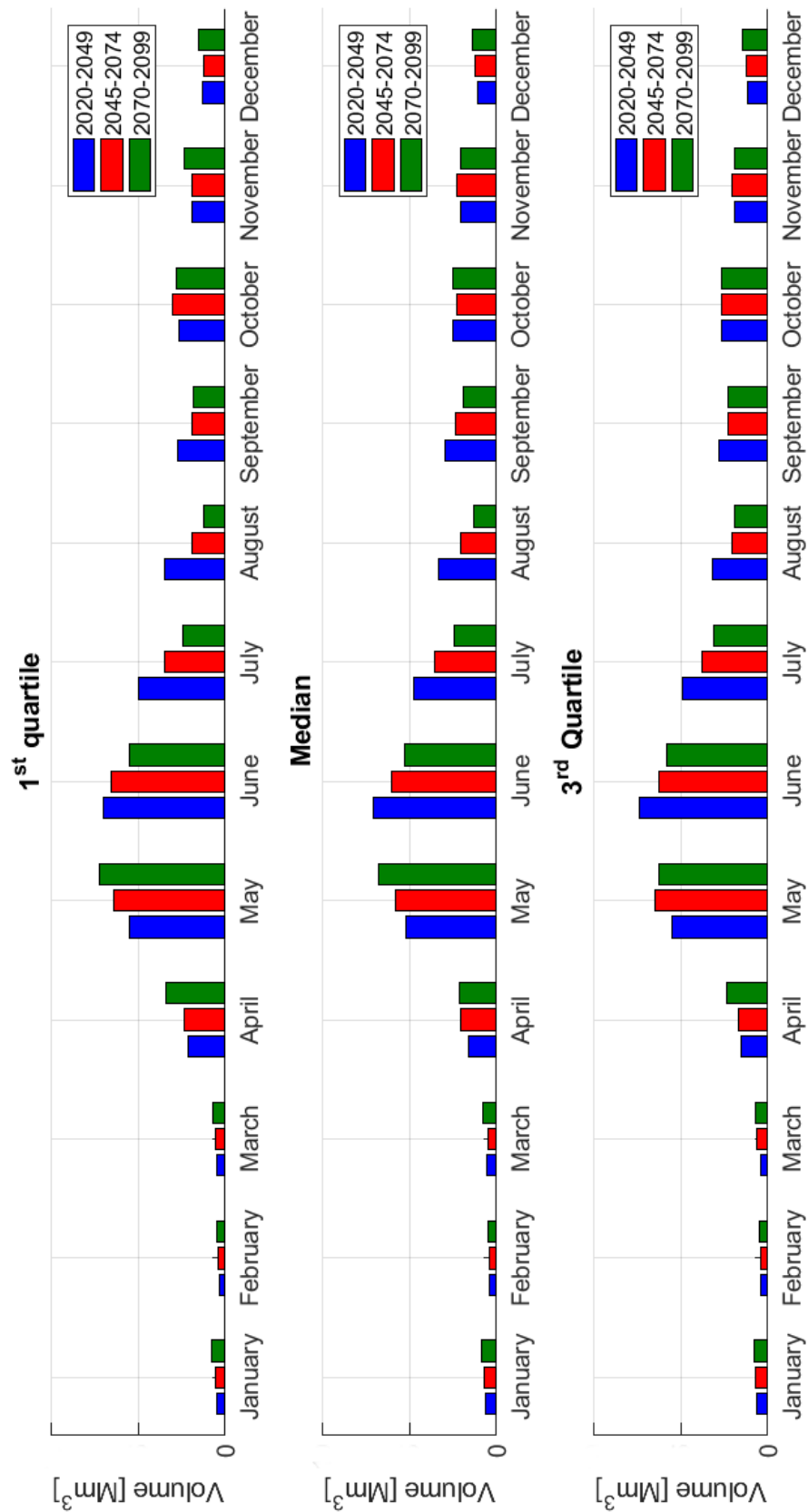


Figure 33 Variation of the water inflow for the next decades with a monthly time step



3.2.4 Performance indicators over the concession period

The variation of the performance indicators over the concession period, using the new hydrology time history are described in Figure 35. The values are all expressed as a percentage and referenced to the current situation. For the annual energy, the new storage reservoir has a small impact and will be reduced in the coming years as the turbined volume will also be irreparably reduced. The annual revenue will increase until 2050 with the new storage reservoir and finally will be reduced in the end of the century.

To determine if the project is profitable, the internal rate of return is computed to estimate the investment's rate of return, see Figure 34. Over an 80-year period, the annuity factor is equal to 3.31% if the interest rate is set at 5% and the inflation rate at 2%. In addition, the operating and maintenance costs rate for the electromechanical and civil equipment was set at 4% and 1.4% respectively. Thus, whatever the hydrological scenario, the internal rate of return is higher than 5% during the first period (2020-2049). However, the lack of water expected by the end of the century drastically reduces the annual revenue and thus makes the renovation option unprofitable for the second period (2045-2074). Finally, only with an optimistic scenario that likely prevents global warming of more than two degrees Celsius since the pre-industrial period, the renovation project is profitable in the end of the century.

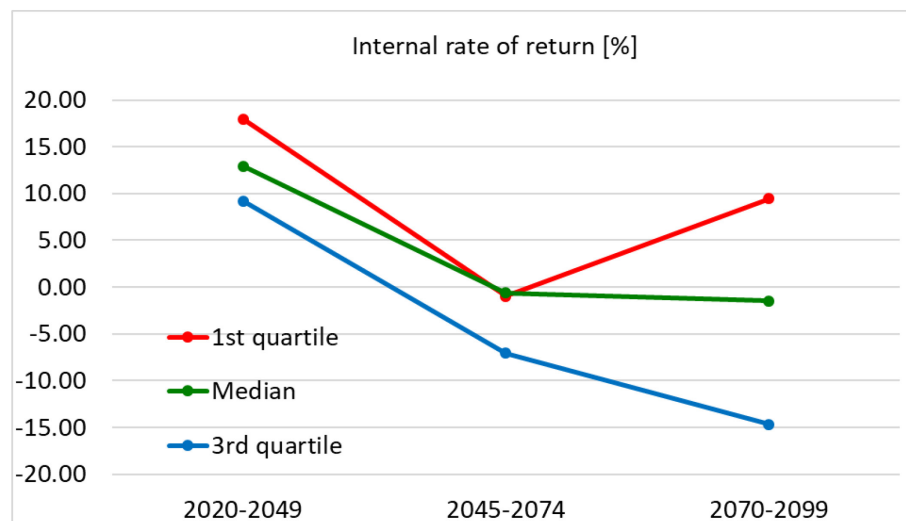


Figure 34 Evolution of the internal rate of return as function of the scenario.

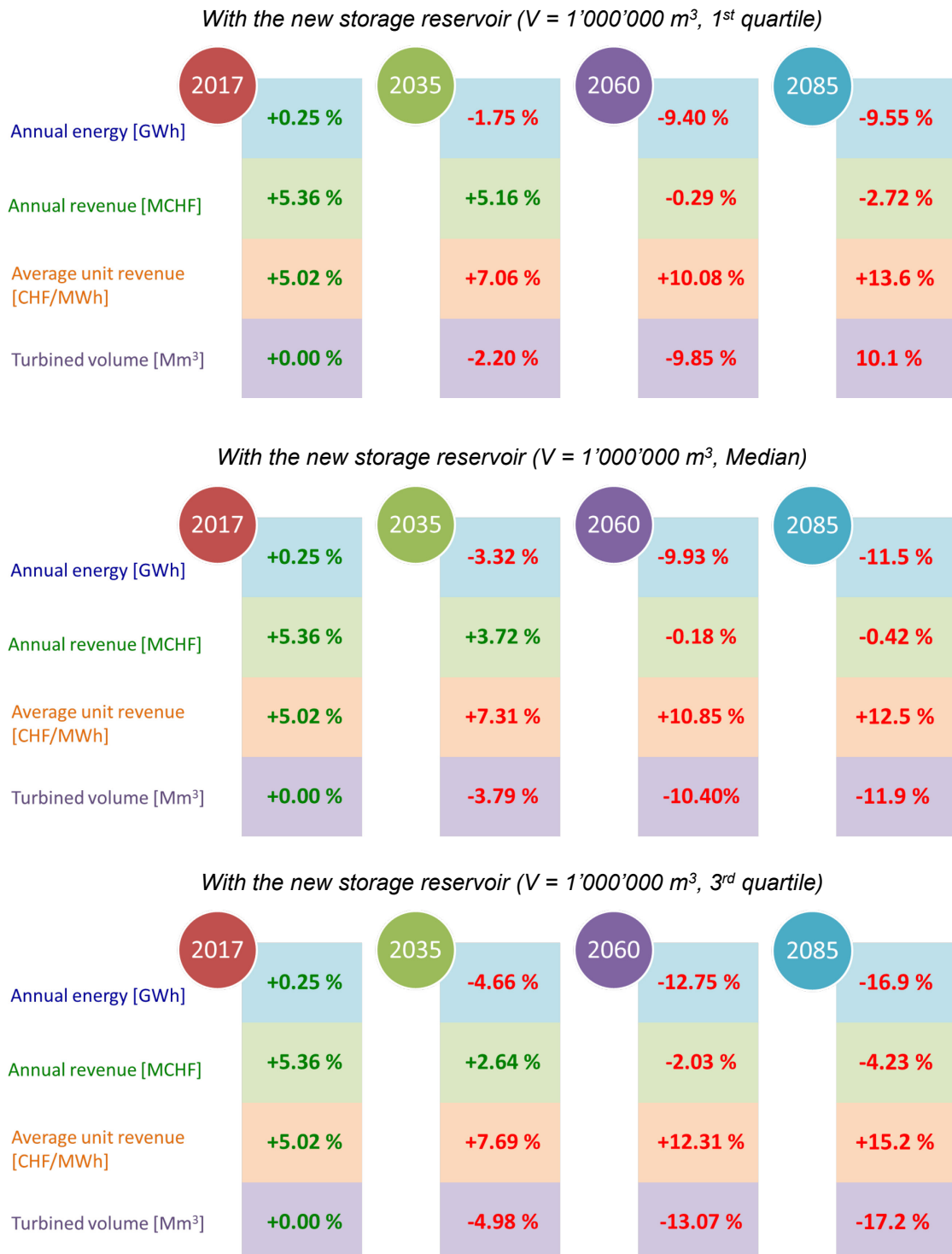


Figure 35 Performance indicators with the current storage reservoir and with the new storage reservoir for the next decades.



3.2.5 Electricity market price in 2030

Since electricity prices decreased in the past years due to an increasing share of renewable energies and low fuel and carbon prices, the return on investment of hydro power plant has decreased. The 3 different electrical scenarios are applied to this renovation option, see Figure 36. As the impact of the hydrological scenarios is very low for the first period (2020-2049), the study was applied only for scenario Medium.

The evolution of the electricity market has a strong impact on the maximum annual revenue that can be provided by the hydraulic power plant. However, since the uncertainty in this electricity market is high and depends on future decision-making by European countries, it is difficult to define the return on investment of a project over the concession period. However, as the computation described in the previous section was performed with the current market price and as the current electricity prices in Europe is low, the value of the internal rate of return is low estimation. The trend in the coming decades would rather be to have more attractive electricity prices and therefore an even better return on investment of the renovation project. However, in order for this project becomes attractive, the electricity price will have to increase significantly in the coming years.

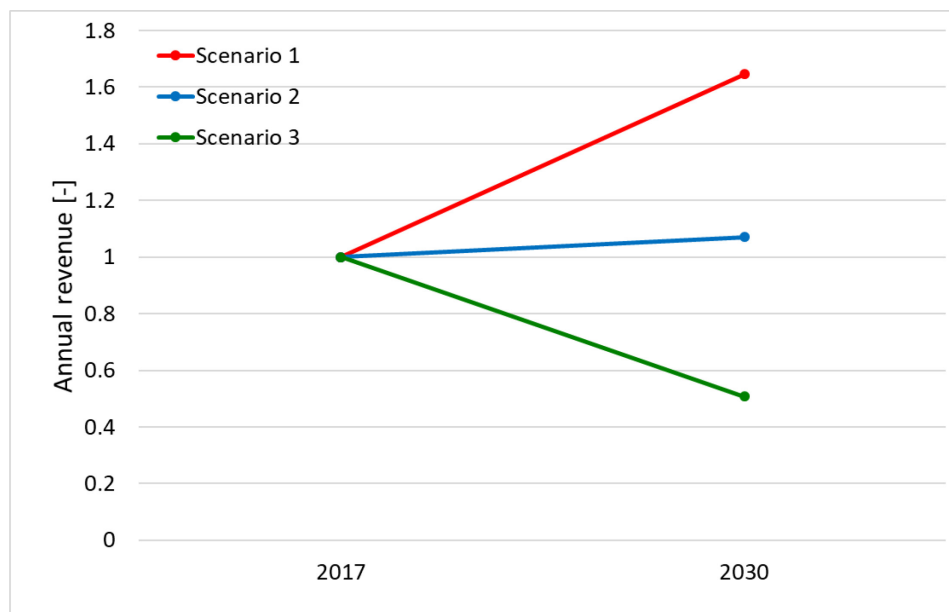


Figure 36 Variation of the annual revenue as function of the electrical scenario (the values are referenced to the annual revenue in 2017)

3.2.6 Conclusion of this test case

The SHAMA project made it possible to take climate change into account in the analysis of renovation option over the concession period. 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. In this particular test case, the increasing of the storage volume allows for a slight increase in the annual revenue until 2050, but the decrease of the precipitation forecast for the second half of this century will not make this project economically viable. A strong increase of the electricity price in the coming year could make this project economically interesting. A pumping solution would be also interesting in order to take advantage of this new storage capacity. **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.**



3.3 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 over the next few decades.

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. Then, the variation of the water inflow will be presented by considering the temperature and the precipitation variations until 2100. Finally, the performance indicators will be computed for the whole century to determine the return on investment of this renovation option.

3.3.1 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 37.
- A released flow in normal operating conditions is applied, see Figure 38.
- 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.

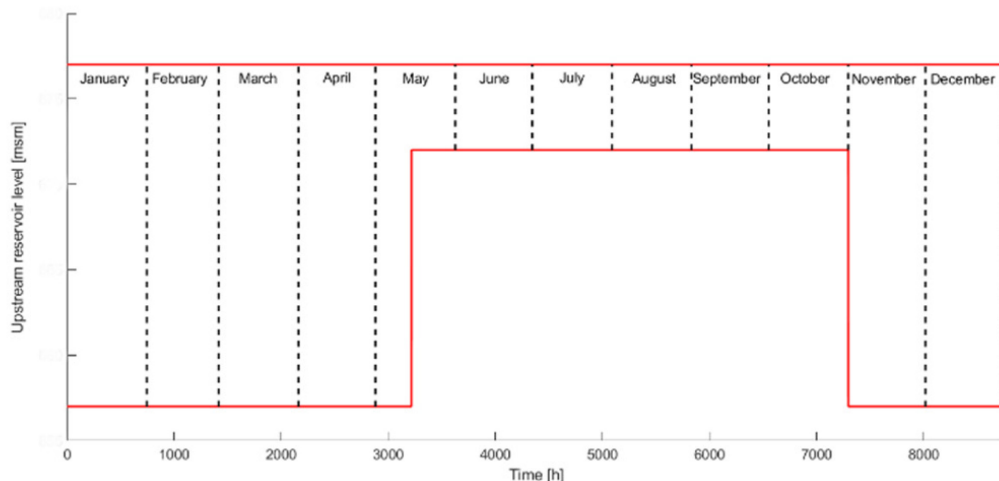


Figure 37 Minimum and maximum water levels in the upstream reservoir throughout the year.

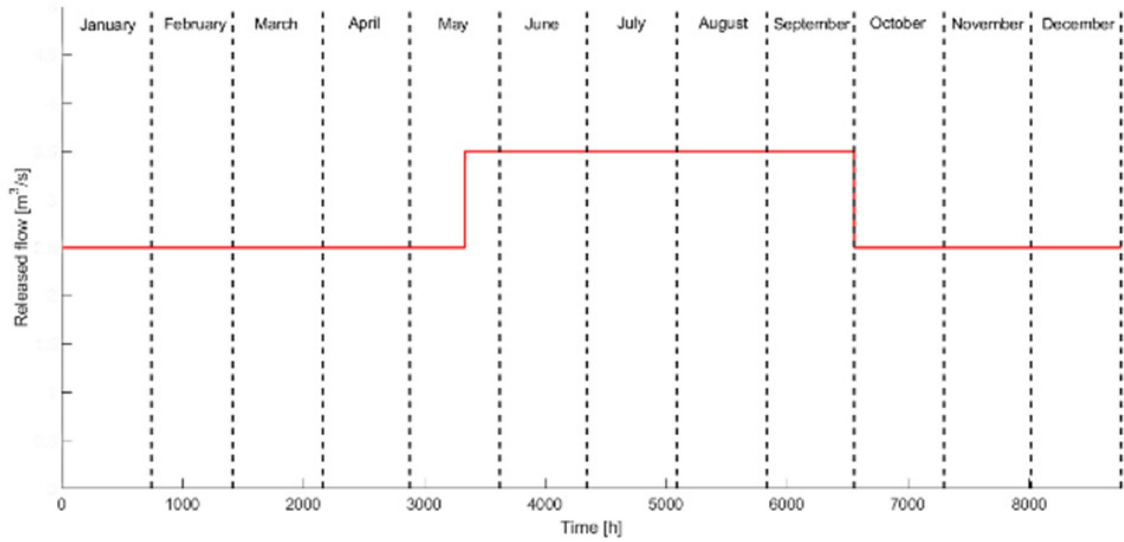


Figure 38 Released flow throughout the year.

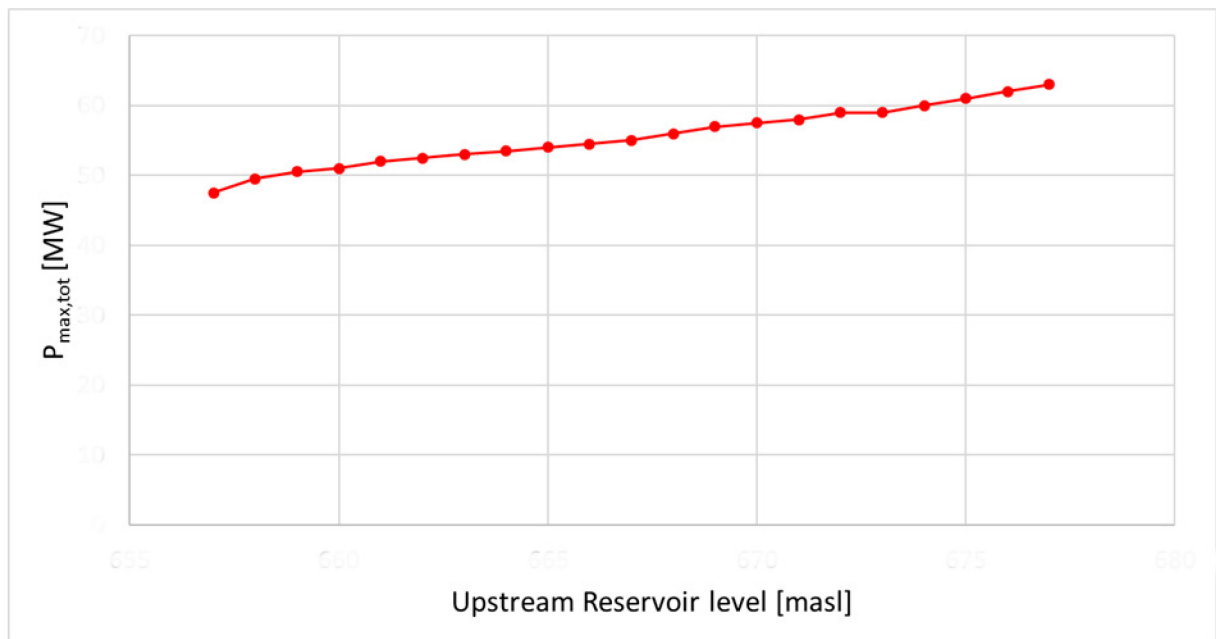


Figure 39 Maximum power set point for the hydro power plant as function of the water level.



3.3.2 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**.

The current values of the performance indicators are set as references and noted 'REF' in the Figure 40. 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, possible outage and climate change over the whole concession duration.

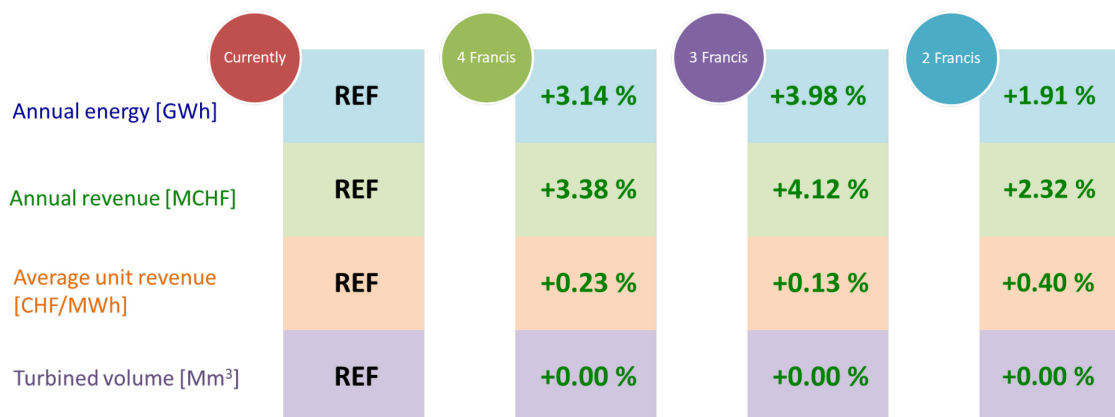


Figure 40 Comparison of the performance indicators between the current situation and the renovation options.



3.3.3 Water inflow for the next decades

The water inflow for the next decades was obtained by the method described in Section 2.2. As reminder, the CH2011 projections assumes two non-intervention emission scenarios (A2 and A1B) that anticipate increases in emission and one climate stabilization scenario (RCP3PD) that supposes emissions are cut by about 50% by 2050.

The analysis of the evolution of the water inflow during the next decades indicates drier months between June and September, thus reducing the total amount of water that can be turbinéd throughout the year. This effect is very pronounced for the scenario A2. Finally, whatever the scenario, the water inflow between October and April remains stable throughout the century, see Figure 41.

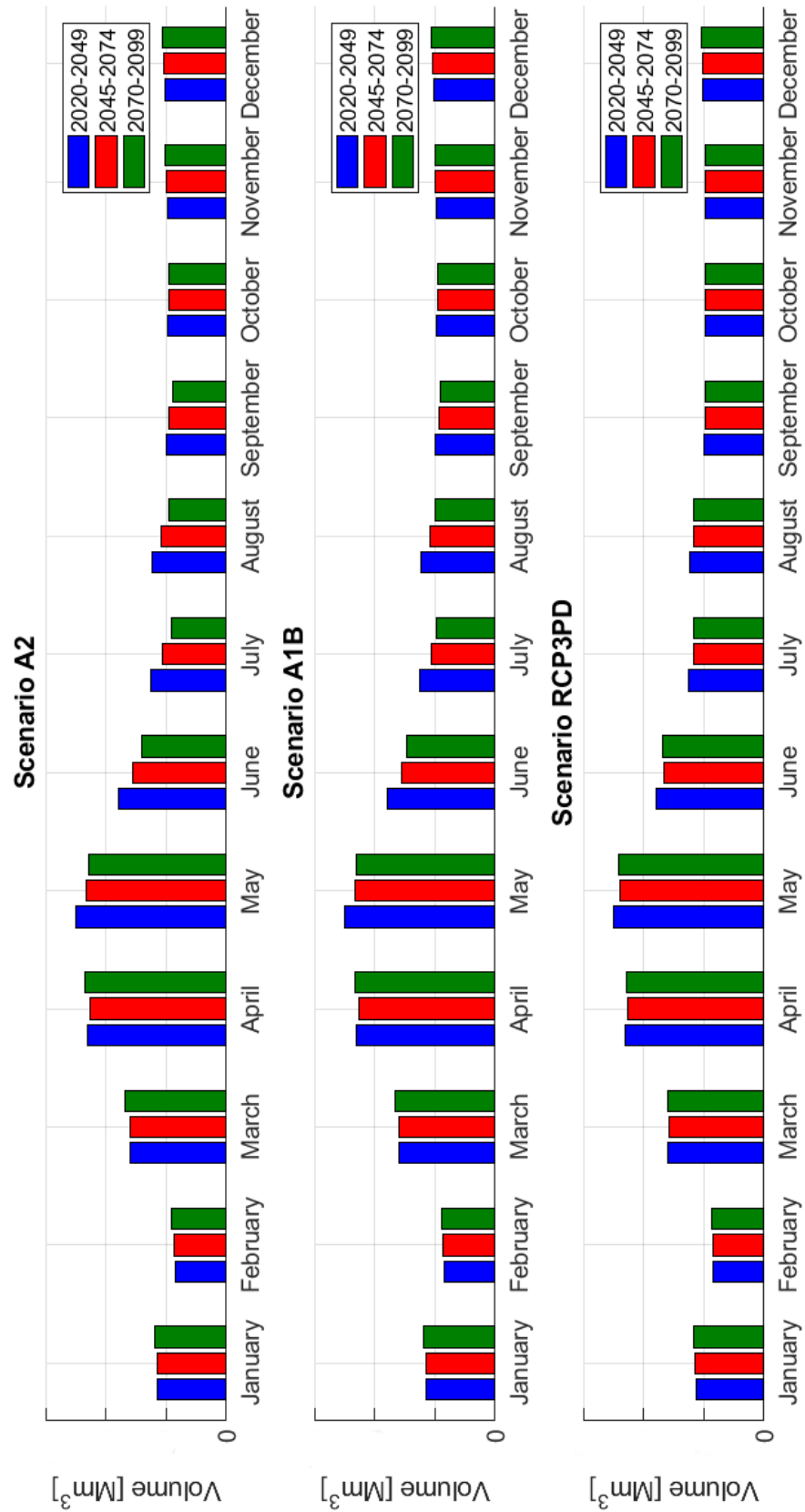


Figure 41 Variation of the water inflow for the next decades with a monthly time step



3.3.4 Performance indicators over the concession period

The variation of the performance indicators over the concession period, using the new hydrology time history are described in Figure 45 for the configuration with 4 Francis turbines, in Figure 46 for the configuration with 3 Francis turbines and in Figure 47 for the configuration with 2 Francis turbines. The values are all expressed as a percentage and referenced to the current situation. The analysis of the annual revenue over the next decades confirms that the configuration with 3 units is the most interesting.

To determine if the project is profitable, the internal rate of return is computed to estimate the investment's rate of return, see Figure 42, Figure 43 and Figure 44 for the different configurations. Over an 80-year period, the annuity factor is equal to 3.31% if the interest rate is set at 5% and the inflation rate at 2%. In addition, the operating and maintenance costs rate for the electromechanical and civil equipment was set at 4% and 1.4% respectively. Thus, whatever the hydrological scenario, the internal rate of return is higher than 5% during the first period (2020-2049). However, only in the most favorable scenario (Scenario RCP3PD), i.e. if global warming remains below 2 degrees Celsius since the pre-industrial period, the renovation option would be profitable in the end of the century.

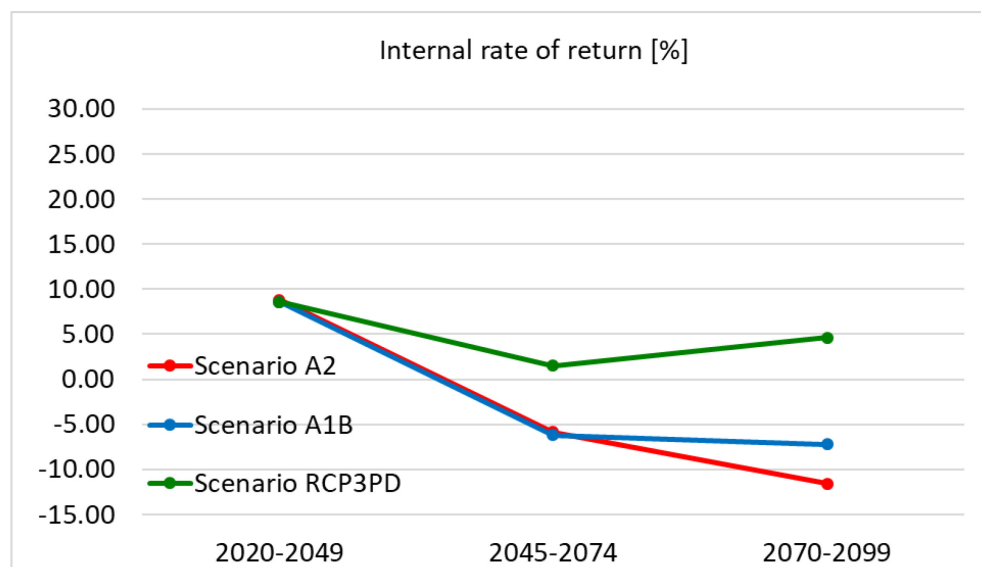


Figure 42 Evolution of the internal rate of return as function of the scenario for 2 Francis turbines.

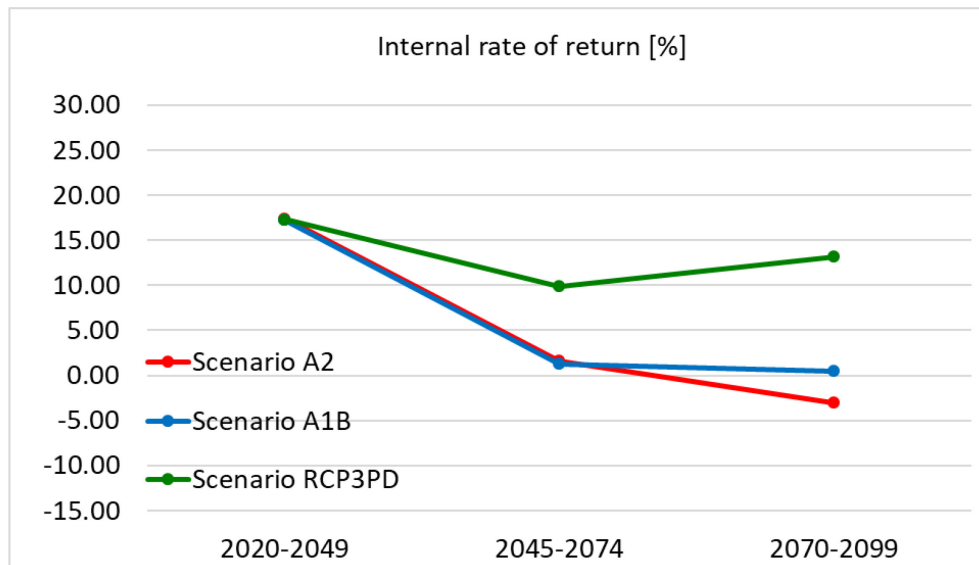


Figure 43 Evolution of the internal rate of return as function of the scenario for 3 Francis turbines.

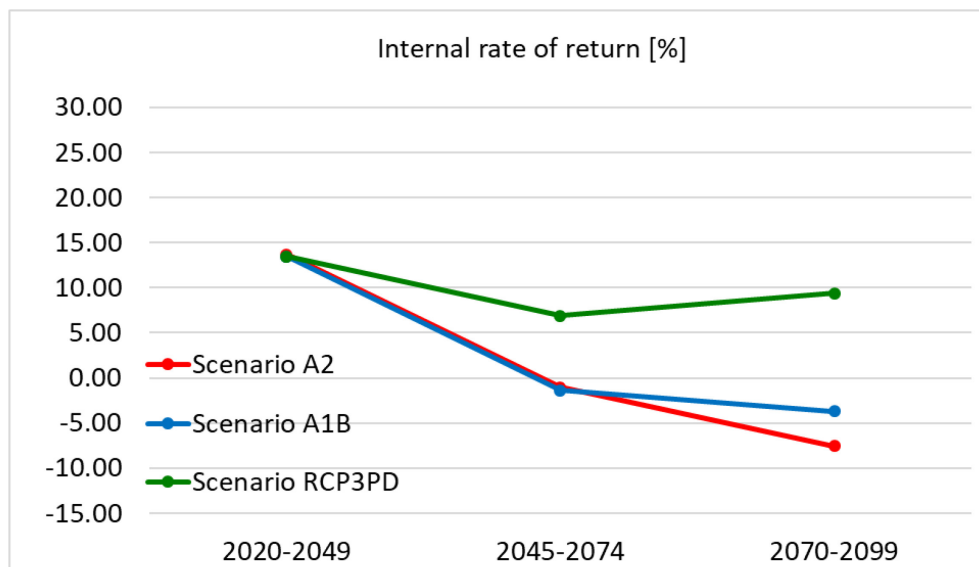


Figure 44 Evolution of the internal rate of return as function of the scenario for 4 Francis turbines.

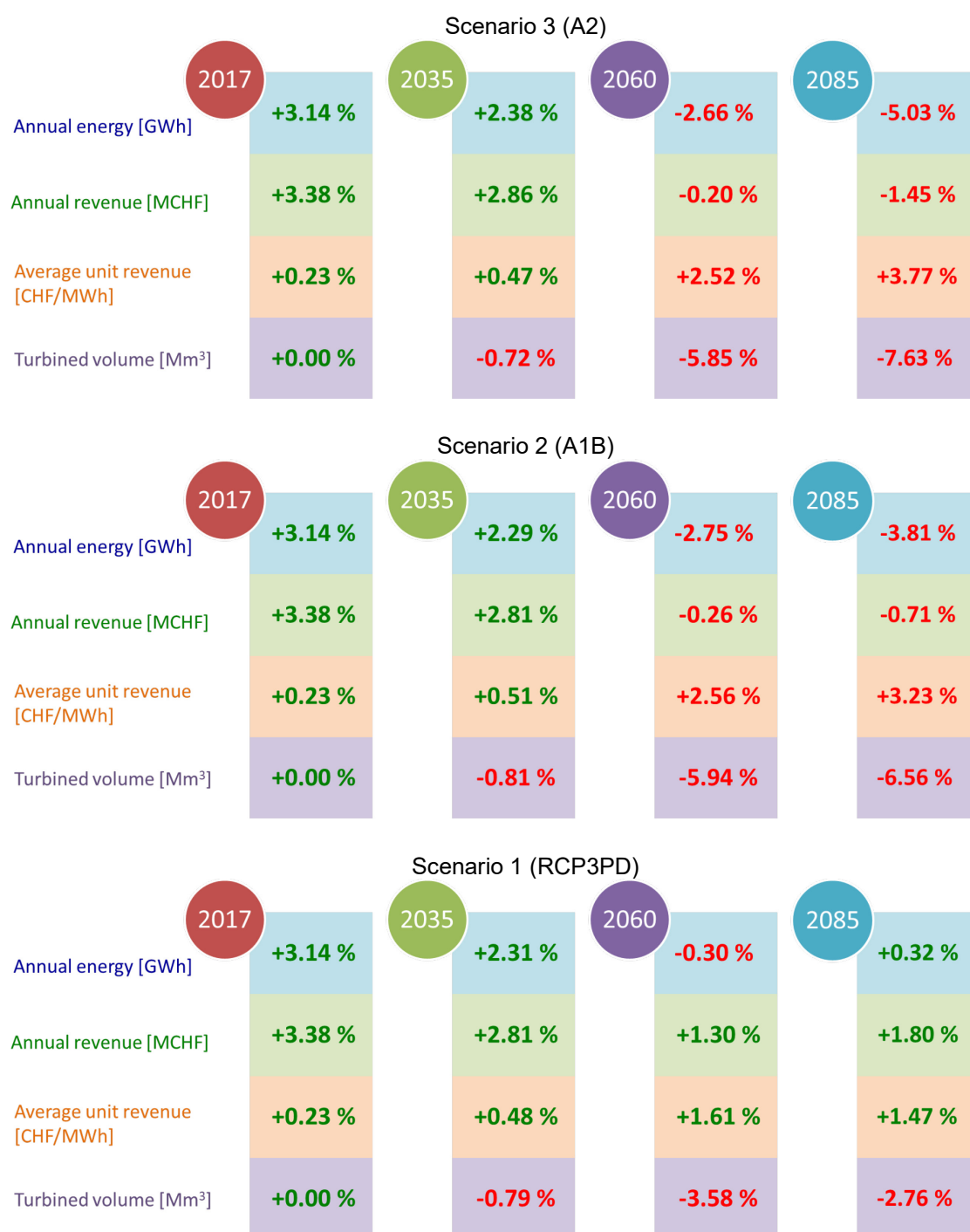


Figure 45 Performance indicators evolution for the next decades with 4 Francis turbines.

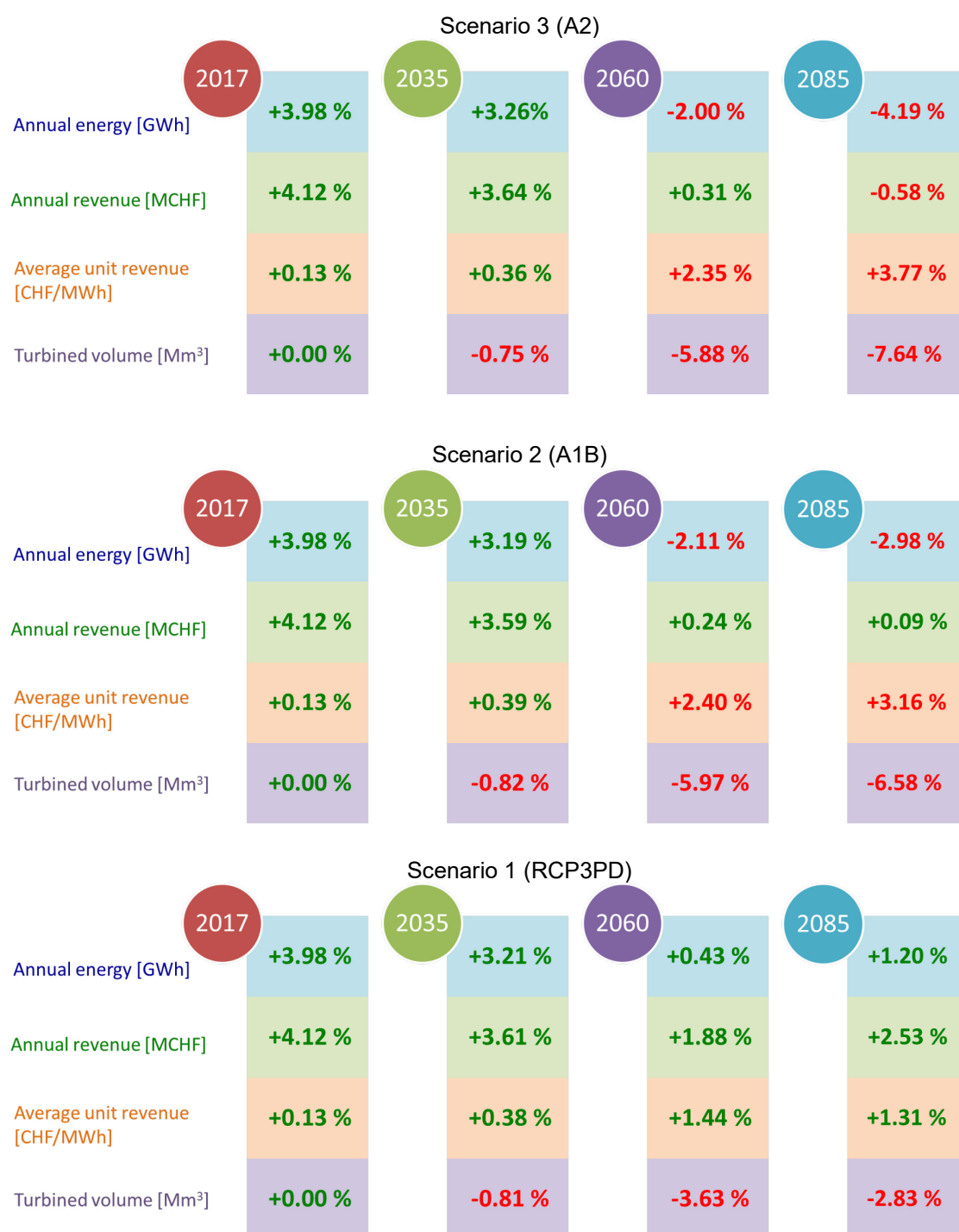


Figure 46 Performance indicators evolution for the next decades with 3 Francis turbines.

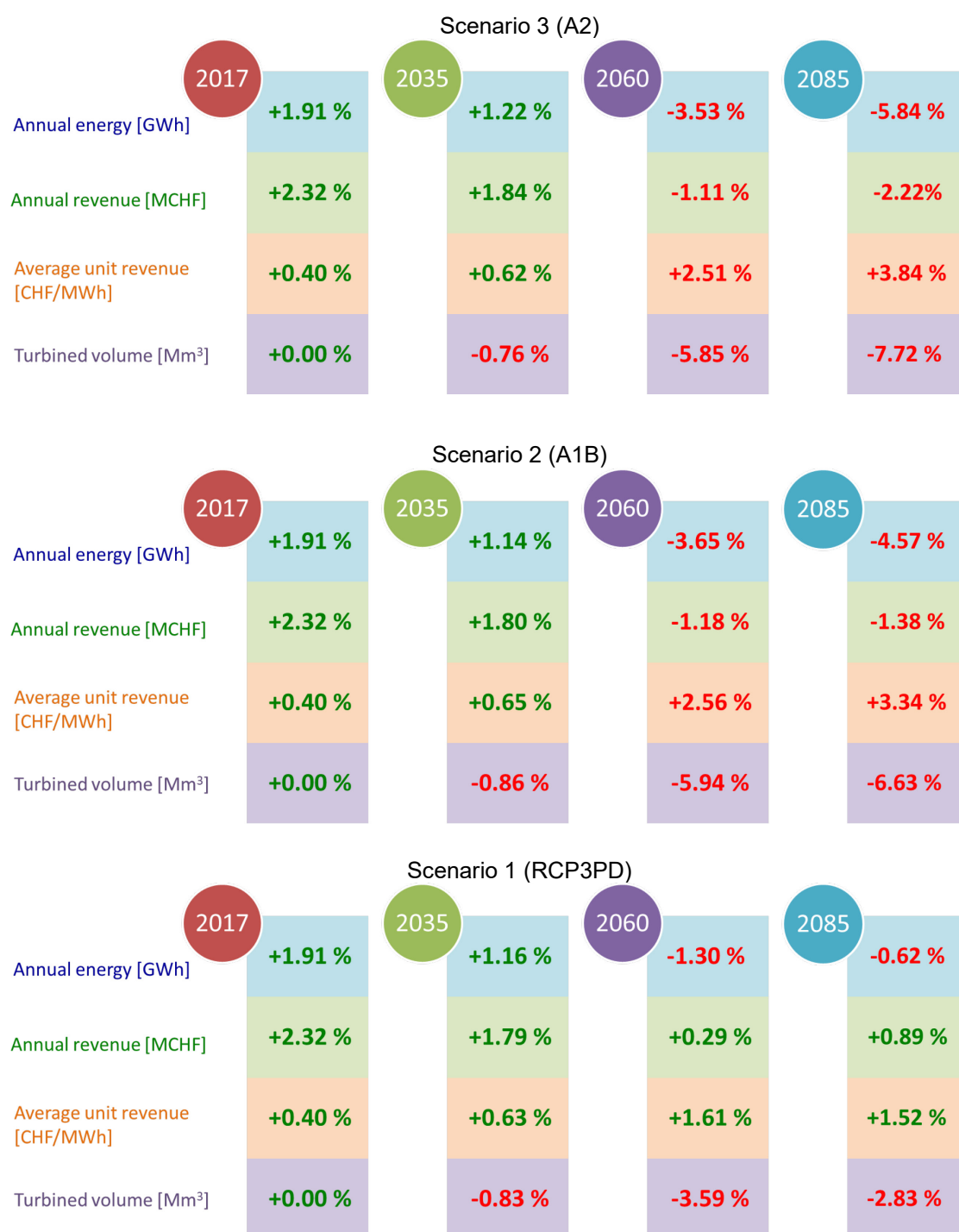


Figure 47 Performance indicators evolution for the next decades with 2 Francis turbines.



3.3.5 Electricity market price in 2030

Since electricity prices decreased in the past years due to an increasing share of renewable energies and low fuel and carbon prices, the return on investment of hydro power plant has decreased. The 3 different electrical scenarios are therefore applied to this renovation option, see Figure 48-51. As the impact of the hydrological scenarios is very low for the first period (2020-2049), the study was applied only for scenario A1B.

The evolution of the electricity market has a strong impact on the maximum annual revenue that can be provided by the hydraulic power plant. However, since the uncertainty in this electricity market is high and depends on future decision-making by European countries, it is difficult to define the return on investment of a project over the concession period. However, as the computation described in the previous section was performed with the current market price and as the current electricity prices in Europe is low, the value of the internal rate of return is low estimation. The trend in the coming decades would rather be to have more attractive electricity prices and therefore an even better return on investment of the renovation project. Thus, if the price of electricity increases slightly in the coming years, this project could become economically interesting.

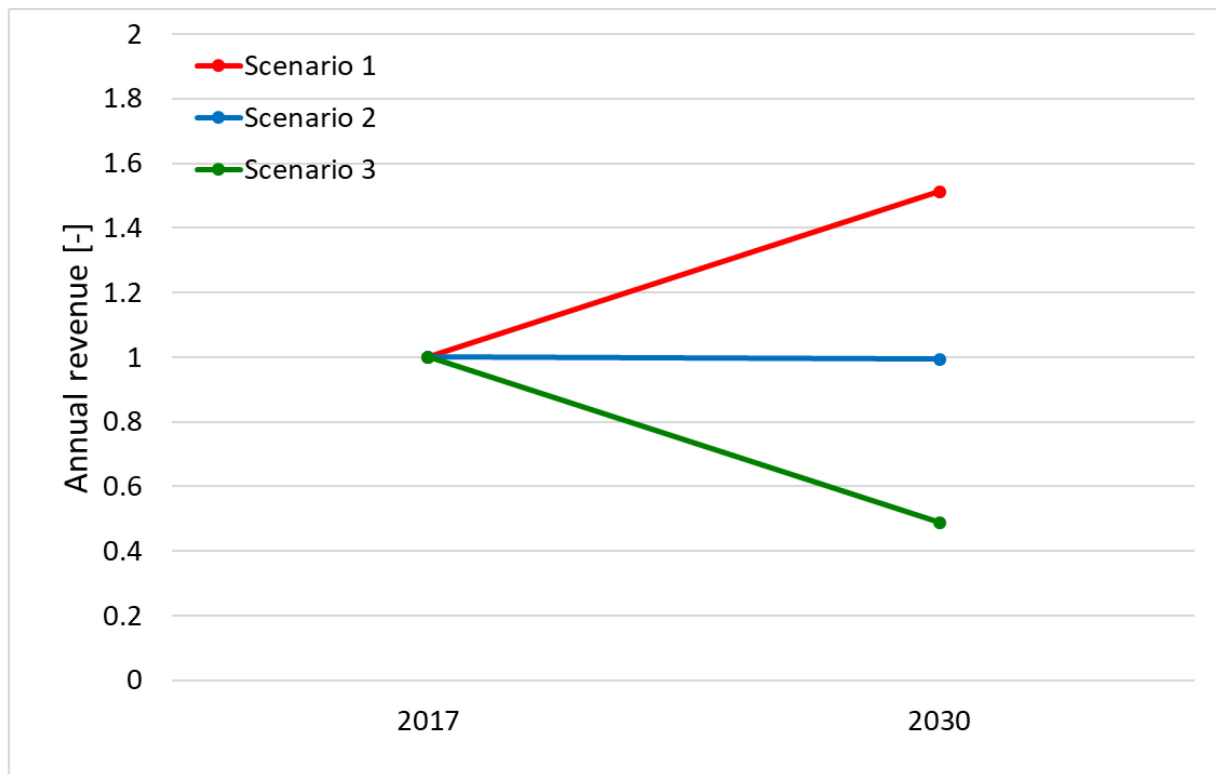


Figure 48 Variation of the annual revenue as function of the electrical scenario (the values are referenced to the annual revenue in 2017) (2 Francis)

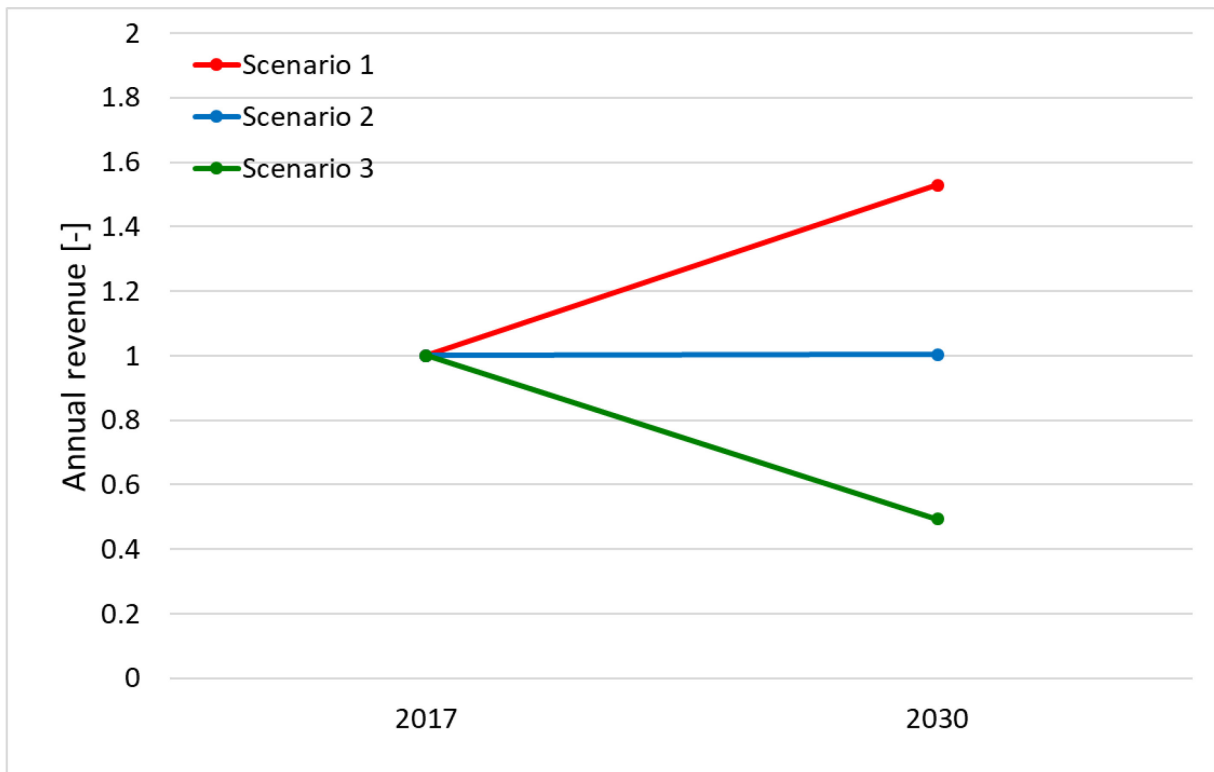


Figure 49 Variation of the annual revenue as function of the electrical scenario (the values are referenced to the annual revenue in 2017) (3 Francs)

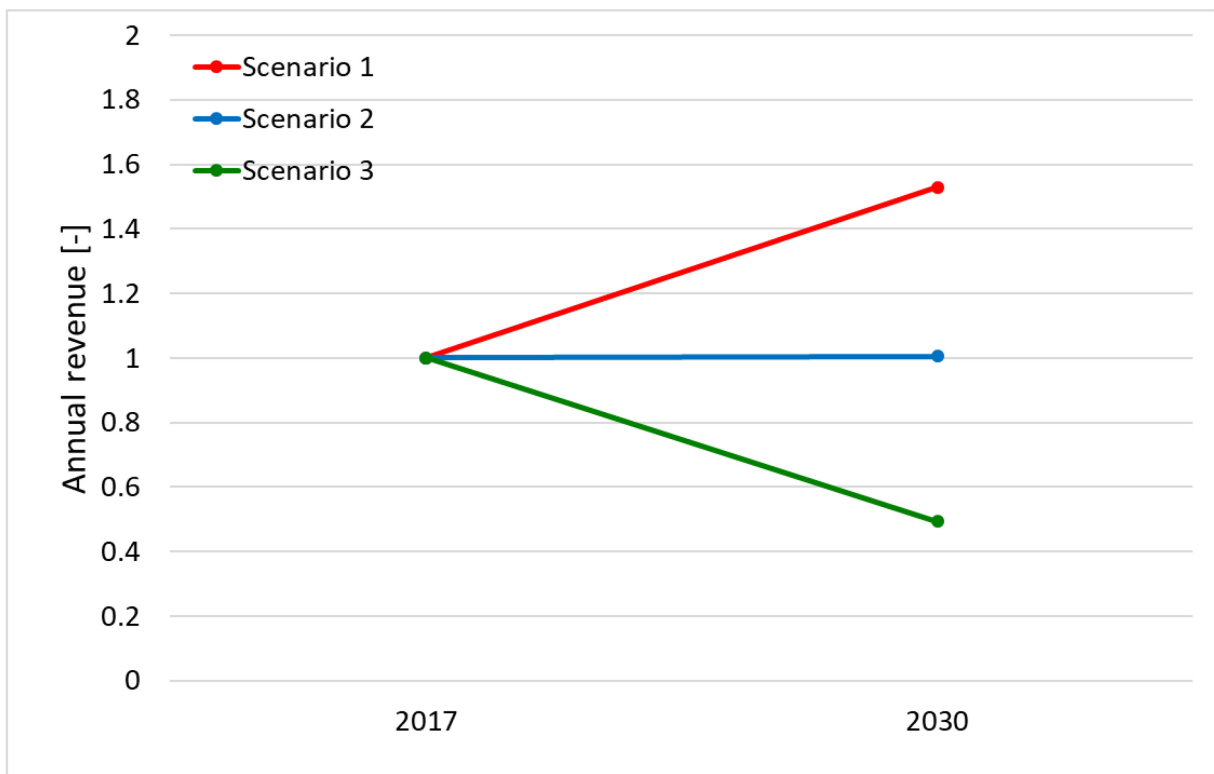


Figure 50 Variation of the annual revenue as function of the electrical scenario (the values are referenced to the annual revenue in 2017) (4 Francs)



3.3.6 Conclusion of this test case

The SHAMA project made it possible to take climate change into account in the analysis of renovation option over the concession period. 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. In this particular test case, the most attractive configuration is a renovation option with 3 Francis turbines. Moreover, in order to ensure a good internal rate of return on this renovation project, it would be interesting if the electricity price will increase over the next decades.

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.



4 Conclusions

The Swiss Hydro Asset Modernization Assessment project (SHAMA) aims at studying the impact of the political, economic and environmental contexts on the best technical solutions for hydropower plant renovation resulting from a systematic assessment process using the RENOVHydro Library. The various Swiss and European political strategies, the evolution of electricity price, climatic changes and environmental constraints are factors that have a direct impact on return on investment of the hydropower renovation for which the best technico-economic solution can be significantly different.

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 turbinized/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. A performance hill chart of the turbine can be selected in a database according to the value of the speed factor, the discharge factor and the year of commissioning. After selecting the reference numerical model, civil engineering and hydroelectric renovation options can be selected. According to the options, the 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.
- For the second step, a hydraulic performance table is computed for each renovation option in order to operate the hydraulic power plant at its maximum performance for a given power set point and a given upstream water level. To evaluate the hydraulic power plant performances over the entire operating range, each unit combination and each guide vane opening combination are evaluated.
- The simulation of a complete year is developed in the third part of the RENOVHydro methodology. To compute production capacity of each renovation option, the electricity market price time history, the hydrology time history, the power and water level limitations are required. To guarantee the best performance of each renovation options, a mathematical optimisation approach is used with a Mixed-Integer Linear Programming algorithm to maximize the annual revenue.
- With transient simulations, the ancillary services and the flexibility of production is quantified and the realistic primary and secondary control potential can be assessed. The performance offered by the renovation options regarding interaction with the electrical power networks, such as primary and secondary control capabilities to determine the maximum load step response compatible with Transmission System Operator requirements, is evaluated.

The Swiss Hydro Asset Modernization Assessment project proposes to assess the influence of the electricity market price and hydrology time history for the next decades in the decision-making process.



- For the hydrology time history, the CH2011 projections is used to determine the changes in temperature and precipitation. The CH2011 projections assumes two non-intervention emission scenarios (A2 and A1B) that anticipate increases in emission and one climate stabilization scenario (RCP3PD) that supposes emissions are cut by about 50% by 2050.
- For the electricity market price history, the power utilities provided 3 different electricity market scenarios for the next decade (up to 2030) based on the scenarios developed by Schillinger et al. These scenarios span a range of low and high price pathways until 2030. The scenarios with high renewable deployment and low carbon and fuel price assumptions describe lower price end. Therefore, the high price scenarios describe high carbon and fuel price assumptions.

This methodology was applied to many case studies throughout the SHAMA project. In particular, 3 studies have been described in detail in this document: two with run-of-river power plants and one with a storage power plant. The impact of the electricity market on these two types of hydraulic power plant is different:

- **The run-of-river power plants** are running continuously and have to recover their costs given the average market price. Their return on investment strongly depends on the development of the EU generation mix, the global fuel markets and the European Union Emissions Trading System. As Switzerland has no influence on this development, Swiss hydro power plant has to adapt to whatever development will materialize. However, as the current electricity prices in Europe is low, the return on investment of these power plants would be increased in the next decades.
- **The storage power plants** are focusing on high price peak load hours and thus have to recover their costs in fewer hours during the year. The participation on balancing markets could provide a significant revenue increase and thereby partially mitigate the overall decline in prices.

For the hydrology time history, most probabilistic projections indicate a reduction in water inflows by 2050 and therefore a reduction in annual energy and annual revenue. The internal rate of return for the renovation project will also be reduced and the investments in the refurbishment are currently low. After 2050, the impact of the hydrology depends on the actions of the political decisions of the various European governments in the coming years to prevent global warming of more than two degrees Celsius since the pre-industrial period.

Finally, the SHAMA project made it possible to compare different renovation options and their return on investment for combinations of different scenarios of hydrology and electricity market. This systematic approach objectively compares the best potential of each renovation option and determine their interest over the entire duration of the concession. This approach is particularly interesting with relatively low electricity prices and increasingly alarming global warming.

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.



5 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 related to this new service will have to be added to the MILP algorithm because it has a significant impact on the return on investment of a hydraulic power plant.

Finally, for the hydrology time history, the probabilistic projections could be improved with the CH2018 Climate Change Scenarios. With these new models, a better estimate of climate change could be taken into account and the long-term return on investment of the hydro power plants would be more accurate with a better idea of consequences of the “Dry summers”, “Heavy precipitation”, “More hot days”, and “Snow-Scarce Winters”.



6 National and international cooperation

The SHAMA 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 SHAMA Project research activities with the others SCCER-SoE research projects. Moreover, the SHAMA project is strongly linked to the RENOVHydro Project 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 SHAMA 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.



7 Publications

- [1] 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
- [2] 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.
- [3] 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
- [4] 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.
- [5] Gaertner, V., Chamoun, S., Manso, P., “Les principaux vecteurs d’adaptation d’installations hydroélectriques de montagne en Suisse”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018.
- [6] Giovani, M., Nicolas, A., Manso, P., Schleiss, A., “Rénovation d’aménagements hydroélectriques alpins”, Poster for SCCER-SoE annual conference, Lucern, Switzerland, September 2018.
- [7] 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.
- [8] 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.



8 References

- [1] **Alvarado-Ancieta, C.**, "Project finance: Estimating the costs of E&M equipment", *Water Power & Dam construction*, February 2009.
- [2] **Association des entreprises électriques suisses**, "*Grande hydraulique*", février 2014.
- [3] **Betz, R., Cludius, J., Filippini, M., Frauendorfer, K., Geissmann, T., Hettich, P., Weigt, H.**, "Wasserkraft: Wiederherstellung der Wettbewerbsfähigkeit", SCCER-CREST White Paper (1), 2016.
- [4] **De Siervo, F. and de Leva, F.**, "Modern trends in selecting and designing Francis turbines", *Water Power & Dam Construction*, August 1976.
- [5] **De Siervo, F. and de Leva, F.**, "Modern trends in selecting and designing Kaplan turbines", *Water Power & Dam Construction*, December 1977.
- [6] **De Siervo, F. and Lugaresi, A.**, "Modern trends in selecting and designing Pelton turbines", *Water Power & Dam Construction*, December 1978.
- [7] **Filippini, M., Geissmann, T.**, "Kostenstruktur und Kosteneffizienz der Schweizer Wasserkraft", Bundesamt für Energie, 2014.
- [8] **Gaudard, L., Romerio, F.**, "The future of hydropower in Europe: Interconnecting climate, markets and policies", *Environmental Science & Policy* 37, pp.172–181, 2014
- [9] **Gomes Pereira Junior J., L. Andolfatto and F. Avellan.** "Monitoring a Francis Turbine Operating Conditions", *Flow Measurement and Instrumentation Journal*, 2018.
- [10] **Graeser, J.-E.**, "Abaque pour pompes et pompes-turbines réversibles", *École polytechnique fédérale de Lausanne, Institut de machines hydrauliques*, Lausanne, 1978.
- [11] **Gordon, J.L.**, "Hydraulic turbine efficiency", *Canadian Journal of Civil Engineering* 28: 238–253, 2001.
- [12] **Henry, P.**, "Turbomachines hydrauliques », Presses polytechniques et universitaires romandes, 1992
- [13] **Landry, C.**, "Hydroacoustic Modeling of a Cavitation Vortex Rope for a Francis Turbine", *EPFL Doctoral Thesis N°6547*, 2015.
- [14] **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.
- [15] **Lugaresi, A. and Mass, A.**, "Designing Francis turbines: trends in the last decade", *Water Power & Dam Construction*, November 1987.
- [16] **Nicolet, C.**, "Hydroacoustic Modeling and Numerical Simulation of Unsteady Operation of Hydroelectric Systems", *EPFL Doctoral Thesis N°3751.*, 2007.
- [17] **Office fédérale de l'énergie OFEN**, "*Le potentiel hydroélectrique de la Suisse*", juin 2012.
- [18] **Sapin, A.**, "Logiciel modulaire pour la simulation et l'étude des systèmes d'entraînement et des réseaux électriques." *EPFL Doctoral Thesis N° 1346*, 1995.
- [19] **Scherer, M., Schlipf, D. and Sattinger, W.**, "Test for primary control capability", Swissgrid, Version 1.1, April 2011.
- [20] **Schillinger, M., Weigt, H., Barry, M., Schumann, R.**, "Hydropower Operation in a changing market environment – A swiss case study", SCCER-CREST, WP3, 2017.



- [21] **Schlecht, I., Weigt, H.**, "Long Drought Ahead? The Future Revenue Prospects of Swiss Hydropower", SCCER-CREST, WP3, 2016
- [22] **Schweiger, F. and Gregori, J.**, "Developments in pump-turbines", *Water Power & Dam construction*, October 1982.
- [23] **Schweiger, F. and Gregori, J.**, "Developments in the design of bulb turbines", *Water Power & Dam construction*, September 1988.
- [24] Swiss Climate Change Scenarios, published by C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zurich, Switzerland, 2011
- [25] **VSE**, "Beiträge der Erzeugungstechnologien zur Stromversorgung und Stabilität des elektrischen Systems", 2016



9 Appendices

9.1 Validation for the test case 1

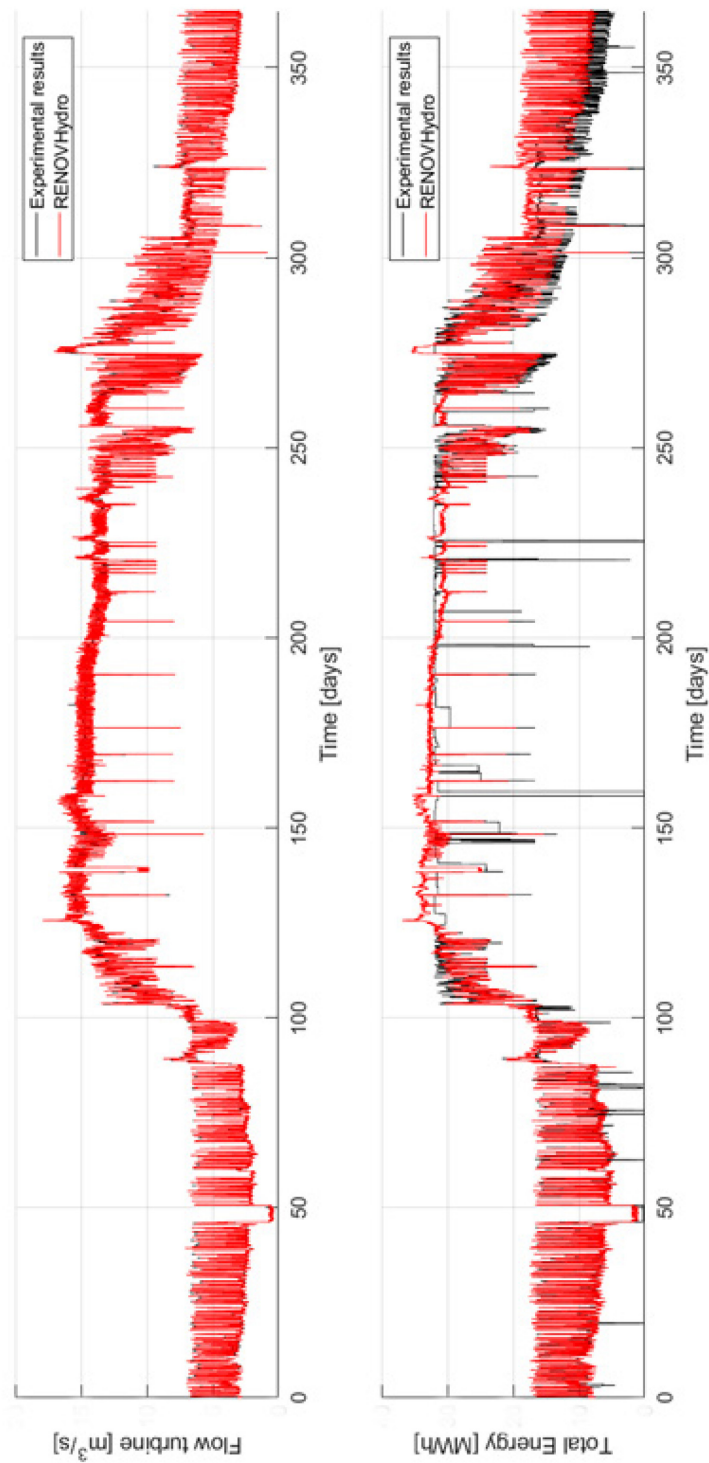


Figure 51 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (black) for the turbined flow and the total energy.



9.2 Validation for the test case 2

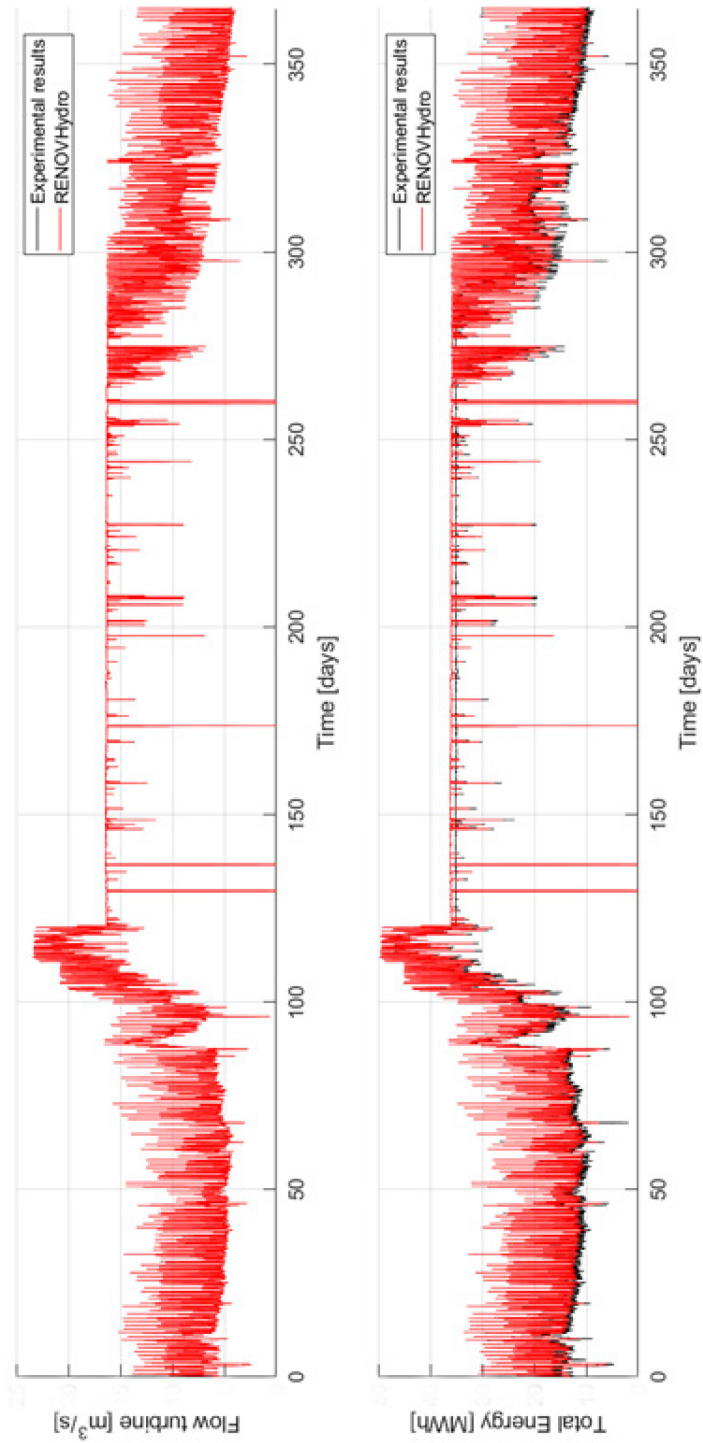


Figure 52 Comparisons between the simulation results obtained with the RENOHydro library (red) and the experimental measurements (black) for the turbined flow and the total energy.



9.3 Validation for the test case 3

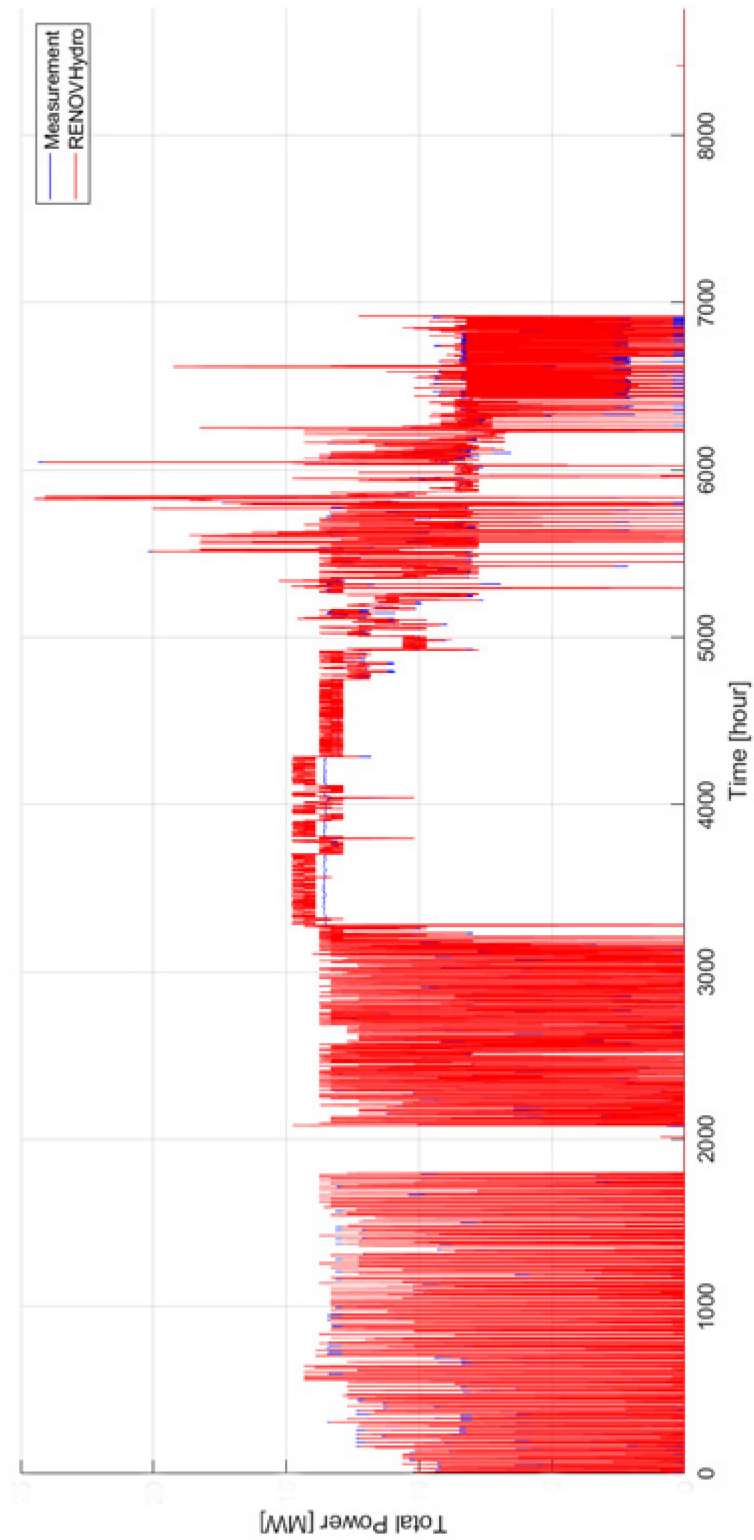


Figure 53 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (black) for the total energy.

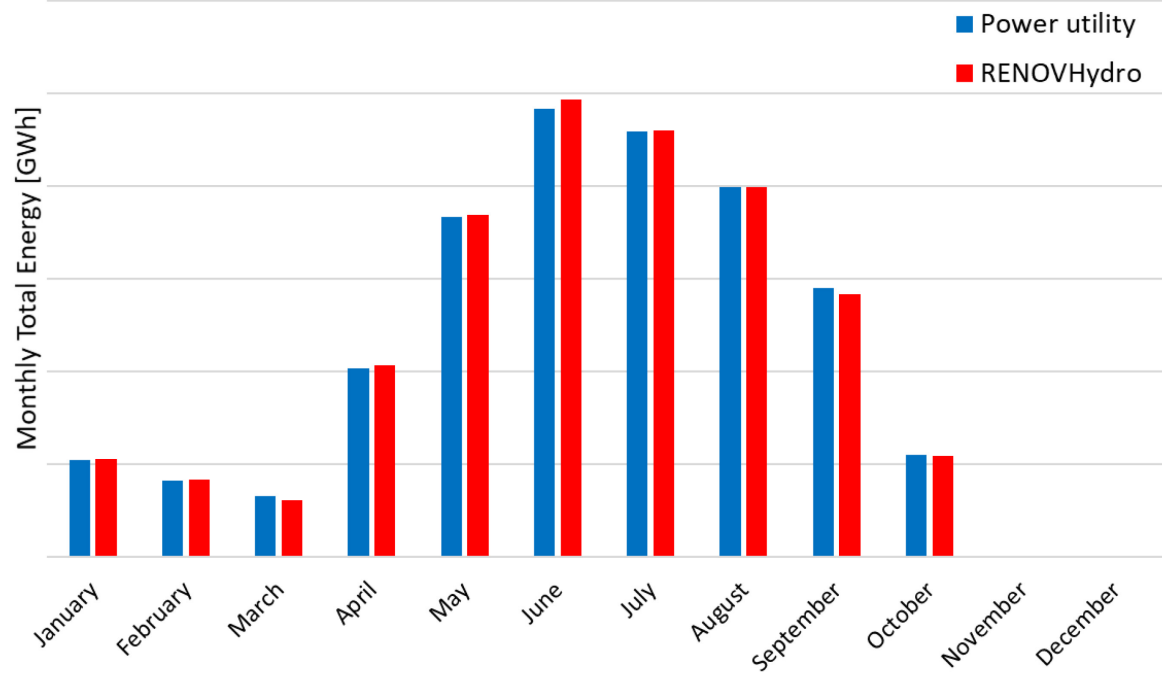


Figure 54 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.

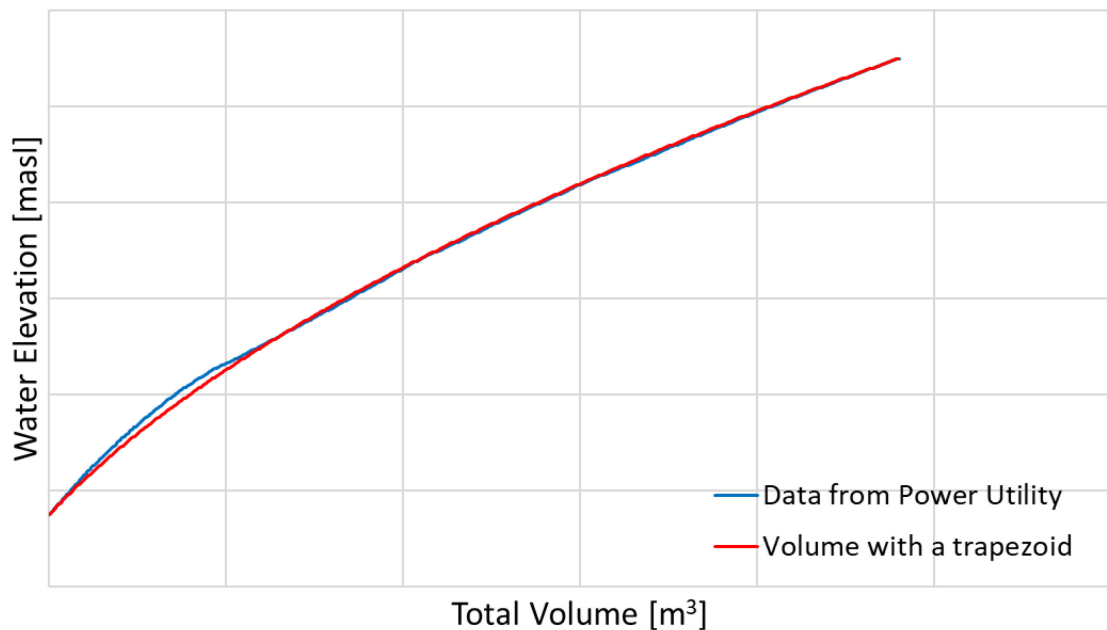


Figure 55 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total volume as function of the water elevation.



9.4 Validation for the test case 4

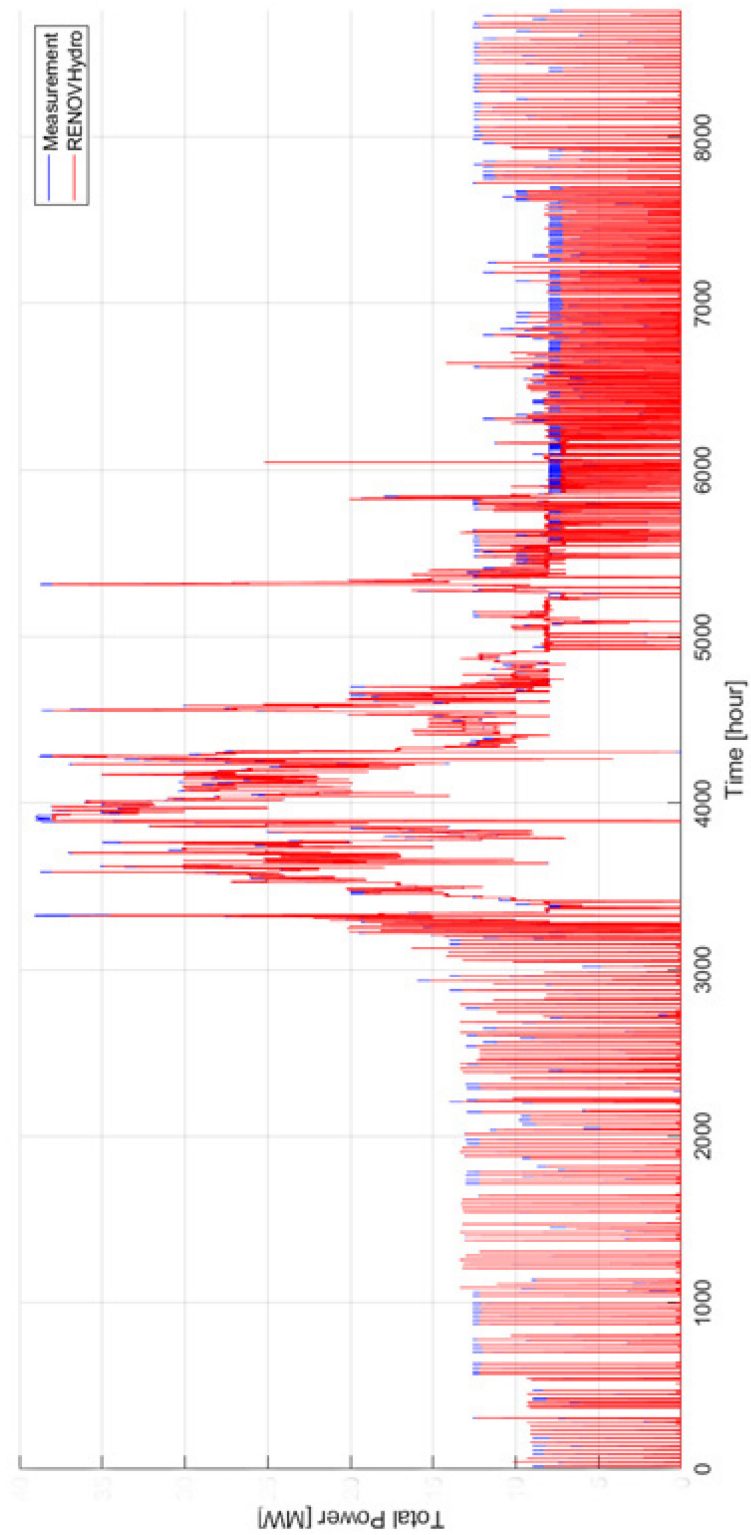


Figure 56 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total energy.

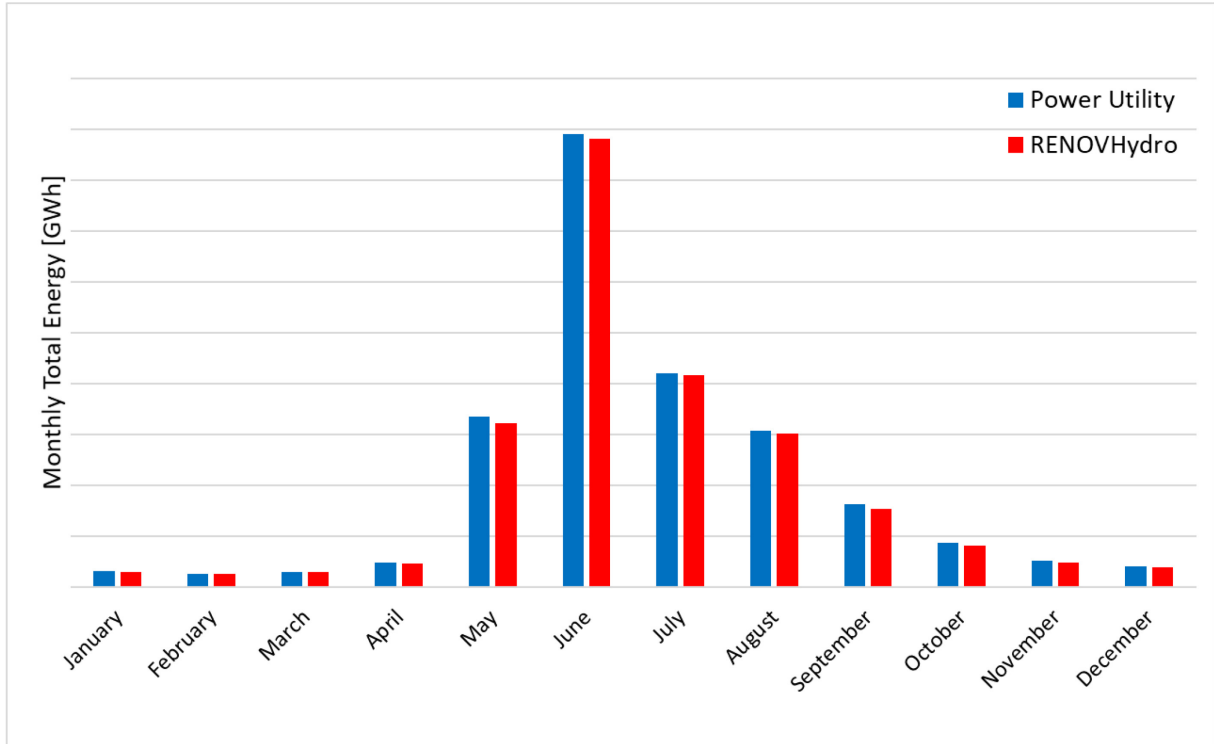


Figure 57 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.

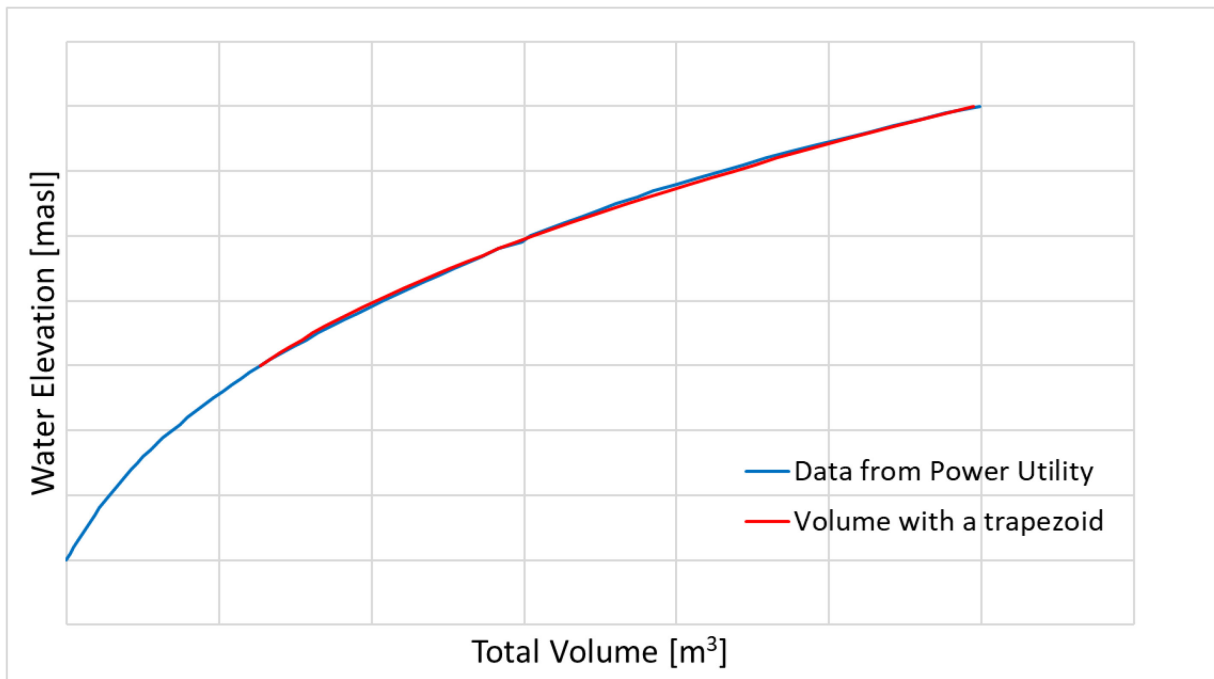


Figure 58 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total volume as function of the water elevation.



9.5 Validation for the test case 5

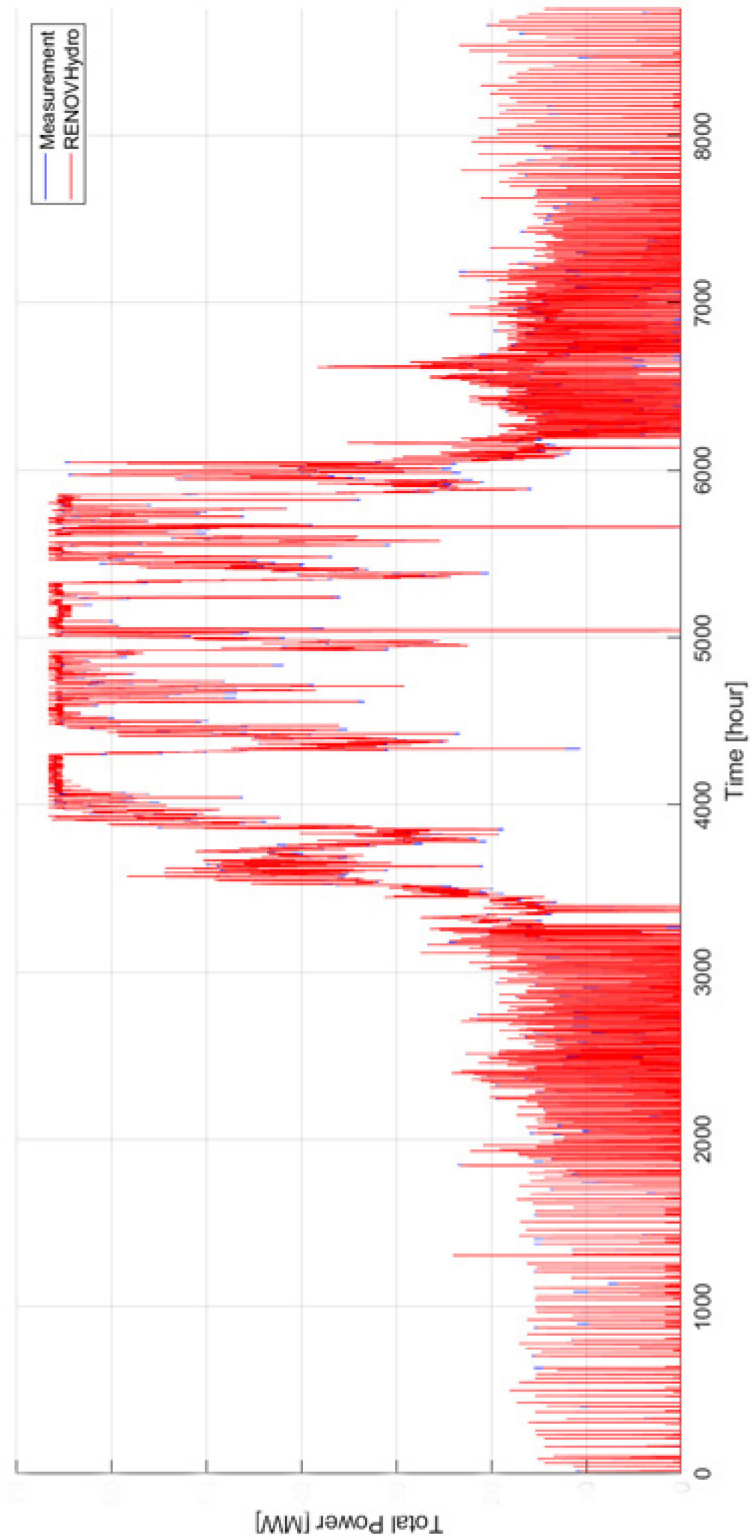


Figure 59 Comparisons between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the total energy.

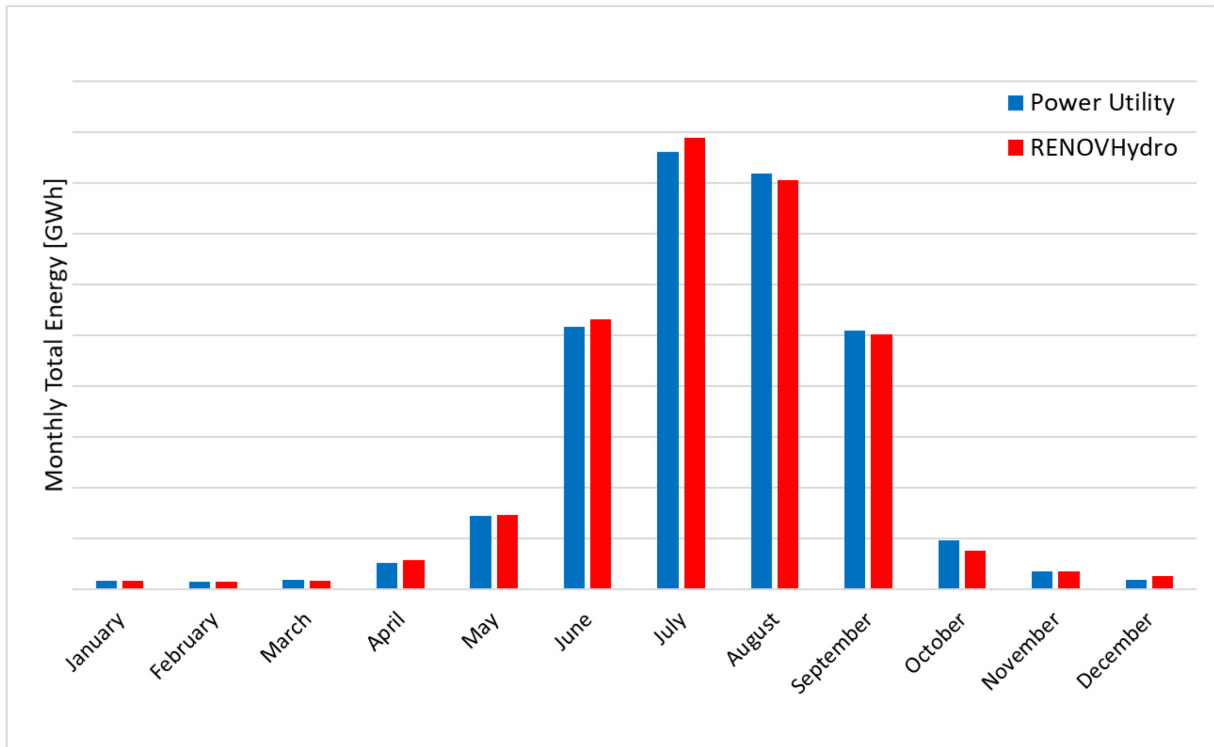


Figure 60 Comparison between the simulation results obtained with the RENOVHydro library (red) and the experimental measurements (blue) for the monthly total energy.