# Optimizing hydro production with a detailed simulation model

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**The increasing demand for electrical energy emphasizes the need for improving the energy output of hydro plants. This can be achieved efficiently by using a model that simulates in detail both turbine energy production and sources of energy losses. This way, one can thus optimize total energy production according to powerplant operational constraints. This paper presents a model developed for a 71 MW storage powerplant in Switzerland, involving four Francis turbines. The potential for additional energy output by numerical optimization of turbine operations is clearly outlined and very promising.**

Worldwide projections for the period 2003-2030 predict that electricity consumption will more than double from 14 781 TWh/year to 30 116 TWh/year [EIA. 2006[1]]. Fig. 1 shows the evolution of the sources of electricity generation from 2003 until 2030. To cope with this need, a gain in efficiency in all domains, that is, production, transport, consumption, but also an increase of renewable energy capacity, are required, to limit the development of solutions generating greenhouse gases. It is therefore of great importance to optimize the energy output of every hydroelectric plant.

## 1. Potential to increase energy production at an existing plant

In the field of energy optimization, it is important to consider a hydro powerplant as a whole. For example, the energetic performances should be evaluated by determining the global efficiency defined as follows:

$$_g = \frac{\sum_{j=1}^{n} P_e}{\rho g \sum_{i=1}^{n} Q_i H_{gross\_i}}$$

The global efficiency is the sum of the electrical active power output of each unit divided by the sum of the available hydraulic power for each unit. Therefore,

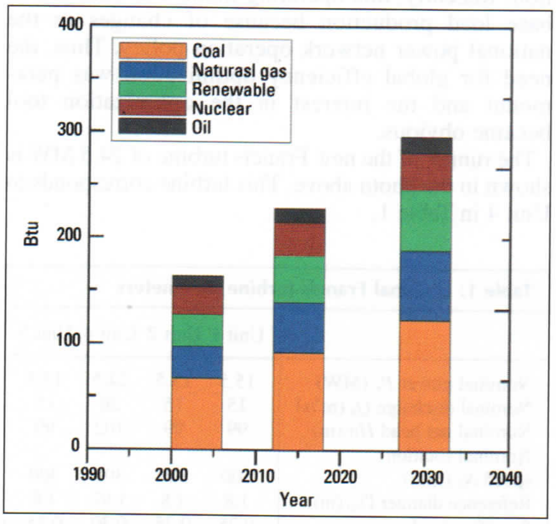



*Fig. 1. Projection of the electricity generation by fuel type for 2003, 2015 and 2030 in BTU (British thermal units) [IEA, 2006[1]].*

determination of the optimal production configuration, that is, the optimal distribution of the power output between all available units, can be achieved using a more elaborate simulation model. Such a model can then be included in a more general optimization procedure, aimed at maximizing the global efficiency, as shown in Fig. 2. To be efficient and reliable, this optimization model should take into account:

- upstream/downstream energy head;
- hydraulic head losses;
- turbines efficiency hill charts;
- generator efficiency; and,
- availability of the units.

This approach is highly desirable when the hydro plant includes turbines with different nominal settings, because the point of highest efficiency is then also different for each turbine. The approach was successfully applied to the Hauterive-Rossens hydro plant in Switzerland, operated by Groupe E SA,

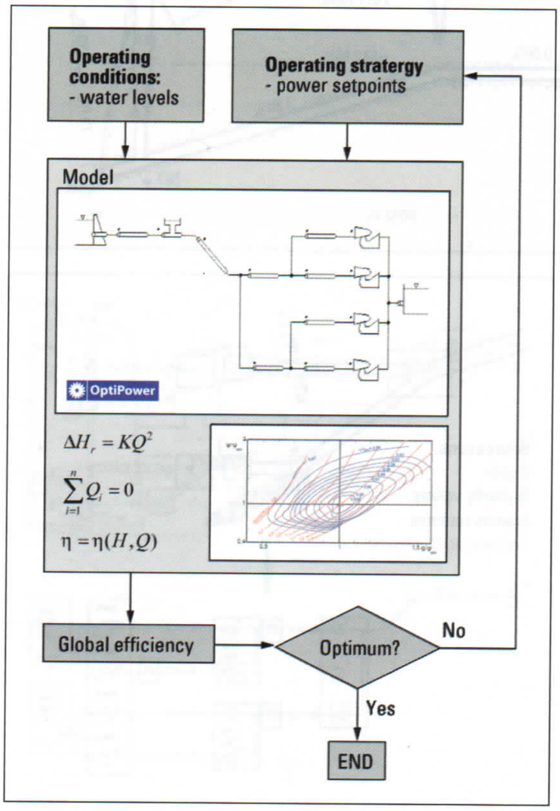



*Fig. 2. The global efficiency optimization procedure.*

*General view of the Hauterive powerplant and (right)the Rossens dam.*

featuring three turbines of 15.5 MW and one new hydraulic turbine of 24.5 MW. The application has been performed in the 'OptiPower' software environment. This generic environment has been specifically developed for simulation and optimization of any kind of complex hydraulic or electrical networks, and allows for the inclusion of all kinds of basic elements, such as reservoirs, galleries, conduits, surge tanks, local head losses, junctions, bifurcations, turbines, pumps, generators, free surface channels, and so on.

The development and the validation of the optimization model of Hauterive-Rossens are presented here. Then, the optimization of one production configuration is also presented and validated with detailed in-situ measurements that have been made available by the powerplant operator.

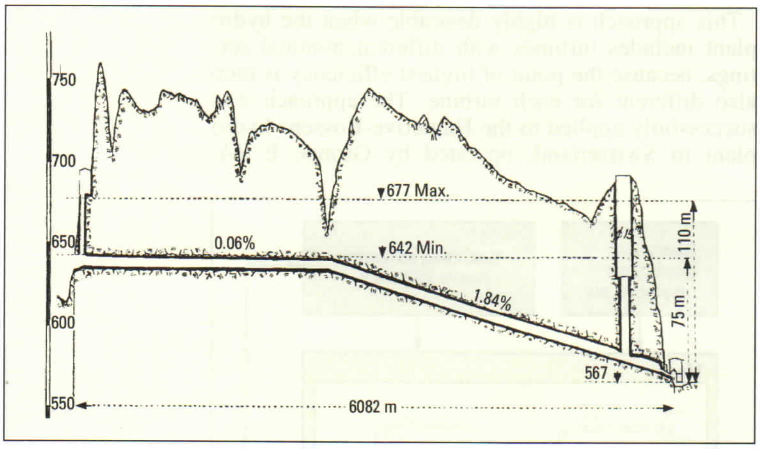



*Fig. 3. The Hauterive-Rossens hydro plant layout.*

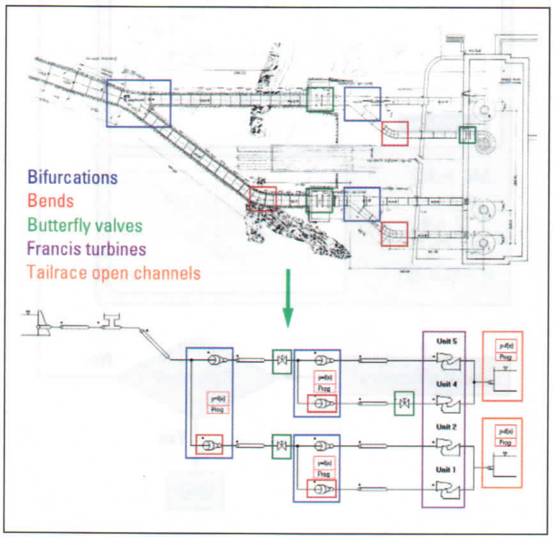
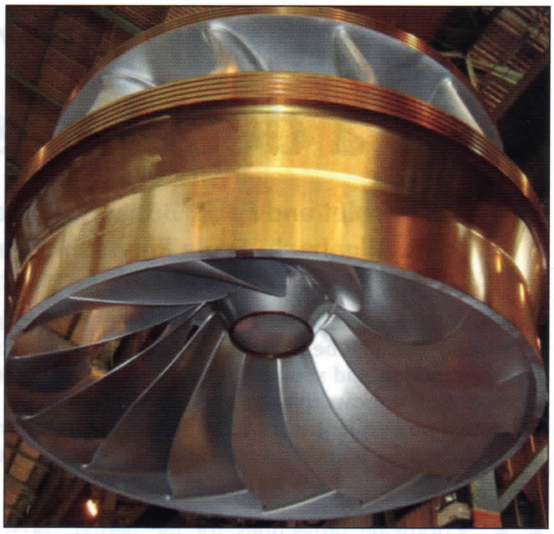



*Fig. 4. Hydraulic scheme of the Hauterive powerplant.*



*The Rossens dam: New Francis runner for Unit 4.*

## 2. Test case: the Hauterive powerplant

The Hauterive powerhouse began operation in 1902 with eight units operating under a gross head of 69 m. Then the dam of Rossens, see photo above left, was built between 1944 and 1948 and connected to the Hauterive power station through a 6 km-long gallery, a surge tank with a diameter of 15 m and finally a penstock with a length of 400 m. The layout of the power plant is shown in Fig. 3.

The powerhouse was then equipped with three 15.5 MW and two 7.5 MW Francis turbines operating under a maximum head of 110 m. In 2007, the two small units were replaced by one 24.5 MW Francis turbine unit.

Table 1 gives the main characteristics of the four units in operation today where the specific speed is defined as:

$$\nu = \omega_n \frac{(Q_n / \pi)^{1/2}}{(2gH_n)^{3/4}}$$

The Hauterive-Rossens powerplant was originally operated to provide energy to control the local power network according to the network demand, which is not compatible with efficiency optimization. Recently, this operating mode was changed to base load production because of changes in the national power network operation policy. Thus, the need for global efficiency optimization was paramount and the interest in the optimization tool became obvious.

The runner of the new Francis turbine of 24.5 MW is shown in the photo above. This turbine corresponds to Unit 4 in Table 1.

**Table 1: Nominal Francis turbine parameters**

| | Unit 1 | Unit 2 | Unit 4 | Unit 5 |
|---|---|---|---|---|
| Nominal power $P_n$ (MW) | 15.5 | 15.5 | 24.5 | 15.5 |
| Nominal discharge $Q_n$ ($m^3/s$) | 15 | 15 | 26 | 15 |
| Nominal net head $Hn$ (m) | 99 | 99 | 102 | 99 |
| Nominal rotation speed $N_n$ (rpm) | 300 | 300 | 300 | 300 |
| Reference diamter $D_{ref}$ (m) | 1.8 | 1.8 | 1.97 | 1.8 |
| Specific speed | 0.25 | 0.25 | 0.30 | 0.25 |

## 3. Modelling of the Hauterive powerplant

The model of the Hauterive-Rossens powerplant has been developed and implemented in OptiPower comprises:

- upstream/downstream head/water level;
- the hydraulic system head losses;
- the turbine characteristics; and,
- the generator efficiency.

These models are described in detail in the next section.

### 3.1 Upstream/downstream water levels

The upstream reservoir of Rossens has a maximum capacity of $173.3 \times 10^6$ m$^3$ for a maximum water level at el. 677. In the context of a daily optimization, this water level can be assumed to be constant. However, the turbines are connected to two open channels on their downstream end. The water level in these channels can be estimated as a function of discharge as follows:

$$H_{Channel} = H_o + B \cdot \ln(Q_{Channel})$$

The constant parameters $H_o$ and $B$ have been determined from measurements on site. The minimum downstream water level is at el. 566, resulting in a maximum gross head of 111 m.

### 3.2 Hydraulic system head losses

The model representing the hydraulic circuit is shown in Fig. 4. The model takes into account the hydraulic system with parallel branches and loops, including both the pipe frictional losses and the singular head losses. The pipe frictional losses are calculated using the Darcy-Weissbach coefficient λ, as given by Streeter and Wylie [1993[2]]:

$$\Delta H_{pipe} = \frac{\lambda L}{2gDA^2} \cdot |Q| \cdot Q$$

The frictional head loss coefficient for the gallery was determined by measurements of the water level in the gallery, while those for the penstock and the manifold were determined according to Idel'cik [1999[3]]. The singular head losses are calculated as a function of a head loss coefficient $K_v$ as follows:

$$\Delta H = \frac{K_v}{2gA_{ref}^{\ 2}} \cdot |Q| \cdot Q$$

The singular head losses considered in this model, see Fig. 4, are generated by: (i) the bifurcations, (ii) the pipe bends, and (iii) the butterfly valves. The corresponding head loss coefficients have been determined according to Idel'cik [1999[3]].

The global set of equations representing the hydraulic scheme has been determined using Kirchhoff laws [Nicolet, 2007[4]; Sapin, 1995[5]], resulting in the following equations for each singular node of the network:

$$\sum_{j=1}^{m} Q_j = 0 \quad \text{and} \quad H_1 = H_j = cste$$

### 3.3 Turbine characteristics

The Francis turbines are modelled using their static characteristics obtained from model testing and defined as a function of the speed factor $N_{11}$, the discharge factor $Q_{11}$ and the torque factor $T_{11}$. These factors are defined as:

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}};\ Q_{11} = \frac{Q}{D_{ref}^{\ 2} \cdot \sqrt{H}};\ T_{11} = \frac{T}{D_{ref}^{\ 3} \cdot H}$$

The resulting theoretical turbine efficiency curve, obtained for a constant net head of 107.5 m, is then compared with related efficiency measurements carried out in 1998 on site for Unit 5. A thermodynamic method was used for these measurements.

A comparison between the simulation model (in red) and the in-situ measurements (in blue) is presented in Fig. 5, and shows good agreement. The same turbine characteristic is considered for the three turbines of 15.5 MW. A similar approach has been considered for the new Unit 4 turbine. However, no efficiency tests have been carried out on the prototype so far. Hence, experimental validation of the turbine characteristic is not yet possible.

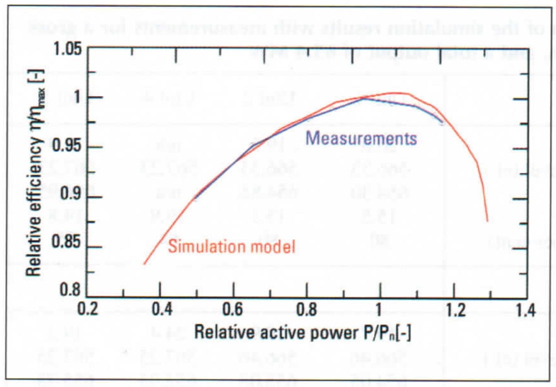



*Fig. 5. Comparison between model and in-situ measurements of Francis turbine efficiency ($H_{net}$=107.5 m, Unit 5).*

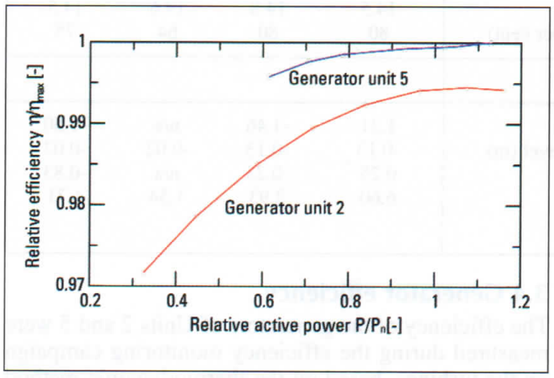



*Fig. 6. Generator efficiency for the different units.*

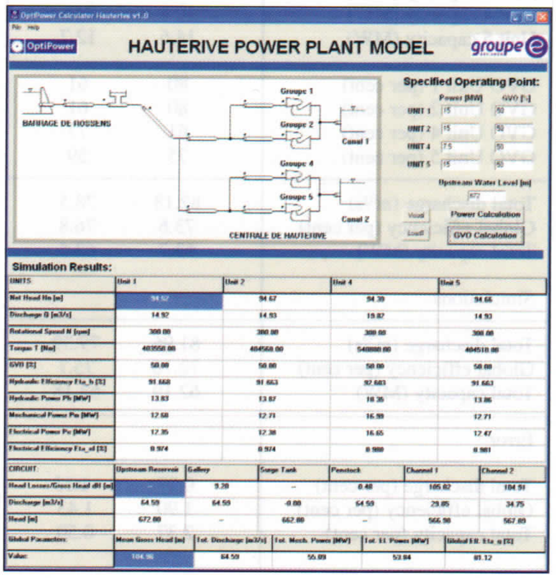



*Fig. 7. General user interface of OptiPower (for the Hauterive powerplant).*

**Table 2: Comparison of the simulation results with measurements for a gross head of about 109 m, and a total output of 65.4 MW**

| Measurements | Unit 1 | Unit 2 | Unit 4 | Unit 5 |
|---|---|---|---|---|
| Discharge ($m^3/s$) | 20.0 | 19.6 | n/a | 18.9 |
| Open channel water level (el.) | 566.33 | 566.33 | 567.23 | 567.23 |
| Inlet pressure (el.) | 654.30 | 654.85 | n/a | 654.95 |
| Output (MW) | 15.5 | 15.2 | 19.9 | 14.8 |
| Guidevane opening (per cent) | 80 | 80 | 64 | 75 |
| **Simulation** | | | | |
| Discharge ($m^3/s$) | 19.7 | 19.9 | 24.4 | 19.2 |
| Open channel water level (el.) | 566.46 | 566.46 | 567.25 | 567.25 |
| Inlet pressure (el.) | 654.05 | 655.08 | 652.93 | 655.78 |
| Output (MW) | 14.5 | 14.8 | 19.6 | 14.5 |
| Guidevane opening (per cent) | 80 | 80 | 64 | 75 |
| **Error** | | | | |
| Discharge (per cent) | 1.31 | -1.46 | n/a | -1.50 |
| Open channel water level (m) | -0.13 | -0.13 | -0.02 | -0.02 |
| Inlet pressure (m) | 0.25 | -0.23 | n/a | -0.83 |
| Output (per cent) | 6.60 | 2.93 | 1.54 | 1.71 |

### 3.4 Generator efficiency

The efficiency of the generators of Units 2 and 5 were measured during the efficiency monitoring campaign on the turbines, based on the thermodynamic method developed in 1998. The evolution of the generator efficiency as a function of the active output power is shown in Fig. 6. The efficiency curve of Unit 2 was also used to model the generator of Unit 1, while efficiency of the new generator of the Unit 4 was defined according to the manufacturer's specifications.

### 3.5 General user interface

The model of the Hauterive-Rossens powerplant, as represented in Fig. 4. has been embedded in a general user interface shown in Fig. 7. The interface enables the user to specify the upstream water level, and to propose a production strategy for the whole powerplant. Optimal production can then be determined by iterative process.

**Table 3: Comparison between strategies 1 and 2**

| Measurements | Strategy 1 | Strategy 2 |
|---|---|---|
| Lake water level (el.) | 674.27 | 674.27 |
| Unit 1 capacity (MW) | 15.5 | 13.1 |
| Unit 2 capacity (MW) | 15.2 | 12.9 |
| Unit 4 capacity (MW) | 18.4 | 24.8 |
| Unit 5 capacity (MW) | 14.6 | 12.7 |
| GVO Unit 1 (per cent) | 80 | 61 |
| GVO Unit 2 (per cent) | 80 | 61 |
| GVO Unit 4 (per cent) | 61 | 77 |
| GVO Unit 5 (per cent) | 75 | 59 |
| Total discharge ($m^3/s$) | 82.18 | 78.5 |
| Global efficiency (per cent) | 73.6 | 76.8 |
| Total capacity (MW) | 63.7 | 63.5 |
| **Simulations** | | |
| Total discharge ($m^3/s$) | 81.96 | 79.39 |
| Global efficiency (per cent) | 72.16 | 75.7 |
| Total capacity (MW) | 62.19 | 63.18 |
| **Error** | | |
| Total discharge (per cent) | 0.27 | -1.13 |
| Global efficiency (per cent) | 1.90 | 1.43 |
| Total capacity (per cent) | 2.37 | 0.50 |

## 4. Validation of the model

The results obtained with the optimization model have been compared with measurements on site for the four units in operation. An example of a comparison is given in Table 2. The upper part of the Table presents the measurement results, the middle part the values obtained with the optimization model, and the lower part error estimates.

It can be seen that very low error values are obtained on the discharge, pressure, water levels and power, except for Unit 1, which features an error of 6.6 per cent. The reason for this discrepancy is not yet clear.

Overall, detailed comparison between simulation model and prototype result in a mean error of 3.6 per cent on the active power and of 1.5 per cent on the discharge. These errors are considered satisfactory, and mean that it is possible to carry out energy production optimizations.

## 5. Potential for production increase

The simulation model allows for optimization of the distribution of energy production between the units for a given total specified output power. This approach has been validated by measurements taken on site for two production strategies:

- an operating point resulting from the original production strategy; and,
- the production strategy obtained by optimization using OptiPower. In both cases, the output power was about 63.6 MW. The value to maximize is the global efficiency of the powerplant given for the Hauterive-Rossens plant by:

$$\eta_g = \frac{P_{e1}+P_{e2}+P_{e4}+P_{e5}}{\rho g\left[Q_{channel1}\left(z_{up}-z_{channel1}\right)+Q_{channel2}\left(z_{up}-z_{channel2}\right)\right]}$$

This equation accounts for the fact that there are two different tailrace open channels. Table 3 presents a comparison of the measurements on site realized for the two production strategies (i) and (ii). The simulation results and the related errors obtained with the simulation model are also given in the Table.

**Annotations**

$A$ = pipe cross section ($m^2$)
$D$ = diameter (m)
$H$ = head (m)
$Q$ = discharge ($m^3/s$)
$N$ = rotation speed (rpm)
$P$ = power (W)
$T$ = Torque (Nm)
$g$ = gravity ($m/s^2$)
$y$ = turbine guidevane opening (-)
$Z$ = elevation above a datum (m)
$\nu_s$ = specific speed (-)
n = subscript for rated

It can be observed that the global efficiency of the powerplant could be improved from 73.6 to 76.8 per cent, which means an increase of 3.2 per cent. This significant increase corresponds to the increase predicted by the Optipower simulations. Also, good agreement can be observed between the simulation model and the prototype, in terms of discharge, output power and global efficiency.

## 6. Conclusions

A simulation model of the 71 MW Hauterive-Rossens powerplant was set up for energy production optimization purposes. This optimization model is embedded in the software OptiPower, and covers: the hydraulic circuit head losses according to the circuit layout, the turbines characteristics, the generator efficiency and the tailrace open channel hydraulic characteristics. Moreover, the interface allows the user to define various powerplant operational strategies and to test the efficiency of each strategy. This makes it possible to define the optimal strategy for the powerplant operator as a function of external constraints, such as availability of the units, power demand, degree of filling of the upstream reservoir, flood situations, and so on.

This new simulation model was validated by comparisons with a vast series of measurements carried out on site. The potential for improving the energy production by using the simulation model was validated by optimizing the energy distribution between the four units for an operating point at 63.6 MW output power. A global efficiency improvement of 4.3 per cent was found on site.

Despite the large number of data required for setting and validating the model, the optimization approach presented proved to be very efficient in defining new production strategies. This approach also emphasized the importance of considering the hydro plant as a whole, and not only focusing on the maximum efficiency of each turbine. Last but not least, it showed that existing operational strategies in powerplants may not always be the most optimal ones, even if they have been applied for a long time, and that room for improvement may still be found.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