Pumped storage in Switzerland - an outlook beyond 2000

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Abstract

Hydraulic storage is the most attractive solution for the power modulation of an electric grid. When the natural storage capacity is limited, pumped storage car enhance the modulation cycle.

Switzerland has a long tradition of hydro power generation. Pumped storage plants from the 1920's are still in operation. With the opening of the National electricity market to the European Community, the economic evaluation of new projects will become more favorable to pumped storage on the Continental scale.

This paper offers a general description of pumped storage in Switzerland and a discussion of future developments, both in terms of electric grid management strategies and technical progress of pump-turbine design.

The research documents include the latest National statistics, operation reports and strategic plans of private power utilities and the Federal administration, and development reviews from hydraulic turbomachine laboratories and manufacturers.

1. Background

1.1 Hydraulic pumped storage

The public demand for electric power varies with the rhythm of Human activities. On a typical winter day, the Swiss grid will absorb 6 GW at night and 7.5 GW in daytime. In summer, this would be 4.5 GW at night and 7 GW in daytime. On weekends, the power demand drops by 20 % [15].

It may be difficult for the electric power plants to accommodate these changes in demand. For technical reasons, it is better for nuclear power plants to run at a quasi-steady power on a seasonal basis. Run of the river hydraulic power plants have but a small capacity for peak hour modulation and produce most of their energy in summer, when the demand is lower.

Most of the daily and weekly power modulation is dealt with by hydraulic storage plants. Large capacity dams in the Alps, at altitudes of 1'500 to 2'000 m above sea level, accumulate the water from melting snow and glaciers and deliver it to hydraulic power plants in peak hours.

Pumped storage [1, 10] is considered when natural water input to the storage dams is not sufficient. Water is pumped from the tailwater in low demand periods and let out through the turbines in peak hours. In the course of this process, numerous fosses must be taken into account and lead to an overall efficiency of typically 70 % :

• Transformer, motor and pump losses	efficiency	0.88	
• Penstock losses in pump mode		0.97	
• Leakage / other losses of headwater reservoir and conduits		0.96	
• Penstock losses in turbine mode		0.97	also for natural storage
• Turbine, generator and transformer losses		0.88	also for natural storage
• Overall efficiency of pumped storage cycle		0.70	

Despite these losses, hydraulic pumped storage is the only practical solution for the storage of large quantities of energy. Alternatives such as steam, compressed air, electromagnetic or electrochemical storage systems [10] are not suitable for large scale storage. Switzerland also has geographical advantages for the development of pumped storage:

- Alpine landscape with steep mountains, increasing the head / penstock length ratio and thus reducing penstock friction losses;
- Sound geological conditions, relatively watertight rock reducing leakage losses;
- Inserted in the large European electric grid with dominant thermal power.

1.2 Daily and seasonal power modulation

Figure 1 shows typical power production curves for winter weekdays. The fully adjustable production form storage power plants is separated from the low-adaptation production from thermal and run of the river power plants. The daily modulation of thermal and run of the river plants for 1970 and 1982 were not available, so only the mean values are plotted. The power restored from pumped storage is not separated from the one obtained from natural storage. From 1970 to 1982 [Grande Dixence document], the energy consumption grew from 2'700 GWh to 4'000 GWh. This increase is mostly in the baseline power. The daily modulation is hardly changed. 1995 is clearly different [15] : the optimization of electric grid management through international exchanges results in an increased modulation of power from hydraulic storage plants.

Figure 2 shows typical power production and demand curves for a 1995 weekday in winter and summer [15]. Power is exported when the production exceeds the domestic demand. The energy balance is positive in both examples. In the winter, the Swiss grid absorbs excess power from French nuclear power plants in the low hours, and restores the energy to the European grid in peak hours. On the Continental scale, Switzerland acts like a large scale daily storage system. There is hardly any pumping in winter.

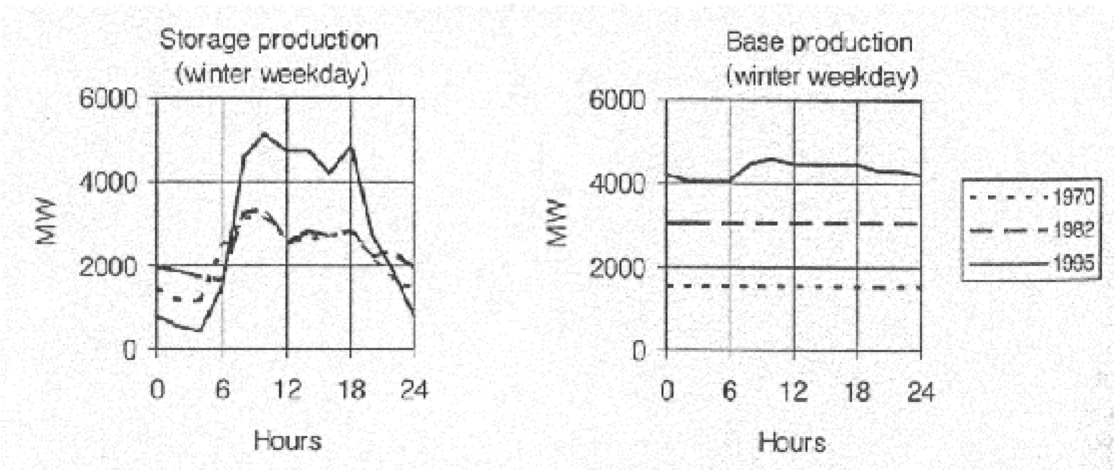


Figure 1 : Daily modulation of electric power production on the third Wednesday of December

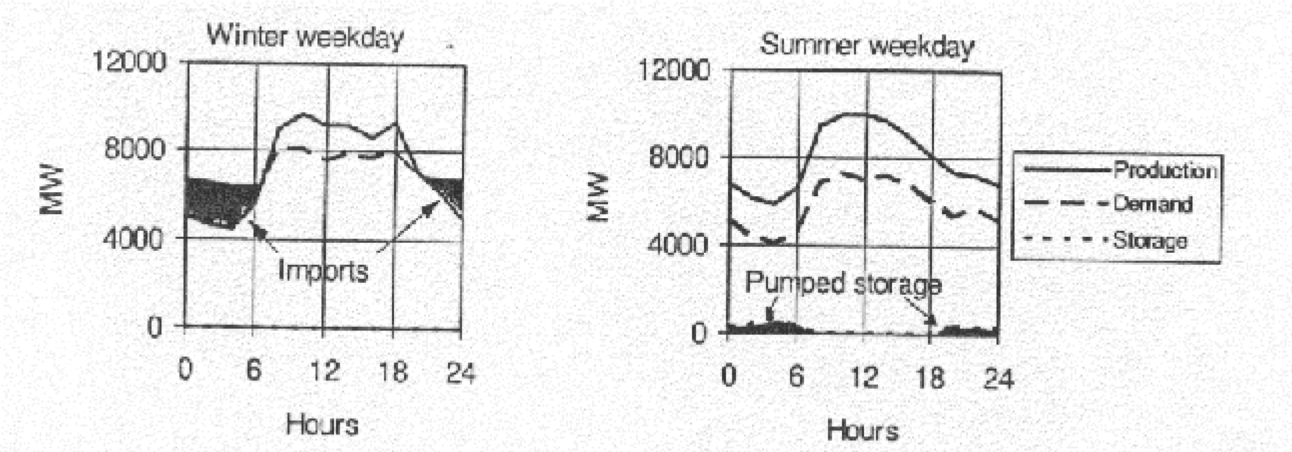


Figure 2 : Daily modulation of electric power demand, third Wednesdays of December and June 1995

In summer, the picture is quite different. There are no electricity imports. Thermal plants are stopped or run at low power. Run of the river plants deliver most of the base power. Storage plants with no seasonal storage capacity do the power modulation. Electric power is exported all day. The pumped storage plants run at night when the power demand on the European grid is low.

1.3 Swiss background for pumped storage

Tables 1, 2 and 3 are based on the 1995 Swiss electricity statistics [15]. With 60'400 GWh, electric energy amounted to 21.5 % of the total energy consumption. The energy absorbed by pumped storage is counted separately from other consumption categories, but the energy restored from pumped storage is included in the energy from natural storage.

Table 1 shows the typical power on the grid with regard to daily and seasonal modulation. Table 2 shows that 32 % of the electric energy was produced by hydraulic storage plants. The mean baseline production of thermal and run of the river power plants does not exceed the mean power demand. Fluctuations of hydro production can cause temporary deficit periods. The energy restored from pumped storage amounts to less than 2 % of the total electric energy production. Table 3 shows the daily and seasonal variation of electric energy exports and imports. Schematically, low hours power is imported from French nuclear power plants and peak hours power is exported to Italy. Imports dominate exports only in the winter low hours.

The People voted in 1990 to suspend nuclear power plant construction for ten years, but chose to keep the existing ones running. To ensure the baseline electricity supply, energy is imported from France. The off-hours imported power amounts to the production of two nuclear power plants. A National energy concept, Energy 2000, was devised to enhance energy savings and the harnessing of renewable energies. 1'418 MW of hydro power are under construction for a future annual production of 621 GWh. 4'250 MW are planned for the coming 30 years for an annual production of 3'630 GWh. The economically feasible hydropower capability, evaluated in 1987, is 37'000 GWh per year [12], but opposition to new hydropower projects on the basis of Environment preservation is getting strong.

GW	95	Peak hours (6 AM-10 PM)		Low hours (10 PM-6 AM)	
		Demand	Production	Demand	Production
Winter	Oct-Apr	7.5	9.5	6	4.5
Summer	May-Sep	7	10.5	4.5	6

Table 1 : Daily and seasonal changes in electric power demand and production on the Swiss grid

Swiss electric production, 1995	GWh	% total
Nuclear power plants	23’500	39
Oil-fired power plants	1’300	2
Run of the river hydraulic power plants	16’200	27
Storage hydraulic power plants	19’400	32
Export - import electric energy balance	7’300	12
Energy absorbed by pumped storage	1’500	2.5
Energy restored from pumped storage	1’100 (approx.)	1.8

Table 2 : Swiss electric energy production, exports and pumped storage figures, rounded to 100 GWh

The positive balance of energy exports will not last. The demand for electric energy resumes growth after the 1991 - 94 recession. It is foreseen that the self-supply index will drop by 8.5 % over the next ten years [9]. Moreover, the beginning of the next century will be marked by the decommissioning of the Beznau (750 MW, year 2012) and Mühleberg (320 M W, year 2013) nuclear power plants.

Swiss electric Companies focus on the production of high-value, peak hours electric power [4, 8]. Presently, pumped storage has a marginal, but not insignificant role in the valorization of low hours electric energy in the summer.

1.4 Swiss pumped storage power plants

Twenty pumped storage plants, listed in table 4, are in operation, for a total pump-mode power of 1'768 MW. These figures cover only schemes in which the gross head is the same in pump and turbine modes. They do not include seasonal storage plants that pump a portion of their water inflow from one high altitude valley to another. The Grande Dixence scheme, for instance, used 314 GWh for pumped storage in 1995 [8], i.e. 20.6 % of the total pumped energy [15], but does not officially qualify as a pumped storage scheme! Storage schemes with auxiliary pumping are listed in table 5.

Figure 3 shows that all of the pumped storage plants are located in the Alpine region, and most of them on the upper Rhone, Rhine, Aar and Maggia rivers.

GWh	Peak hours			Low hours			Global		
1995	Export	Import	Balance	Export	Import	Balance	Export	Import	Balance
Winter	11'900	9'600	2'300	6'200	7'600	-1'400	18'100	17'200	900
Summer	11'600	7'000	4'600	6'500	4700	1'800	18’100	11'700	6'400
Year	23'500	16'600	6'900	12'700	12'300	400	36'200	28'900	7'300

Table 3 : Swiss electric energy exports and imports, figures rounded to 100 GWh

Figure 4 shows how the pump mode power of the Swiss pumped storage plants relates to pumping heads [12]. The superposition of the typical unit cost curve for complete power plants (transposed from [5, 10] shows that the smallest installation costs are found in the 400 to 900 m head range. Thirteen of them lie in this favorable range and amount for 95 % of the pumped storage power.

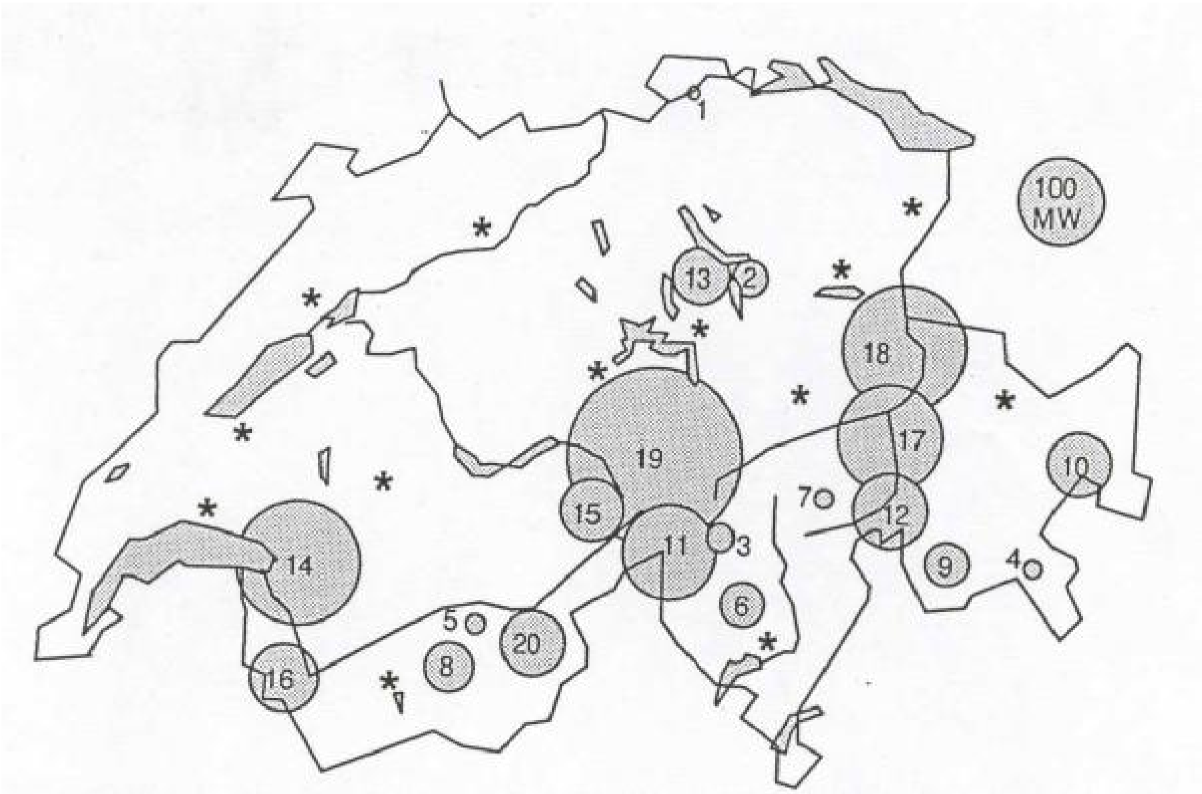


Figure 3 : Swiss pumped storage schemes. The area of circles stands for plant power in pumping mode (data from [5, 12], numbers see table 4). The stars stand for potential new pumped storage sites [5].

Swiss pumped storage plants, by year of commissioning — **Total pump power 1768 MW**

N°	Plant	Year	H, m	P, MW	N°	Plant	Year	H, m	P, MW
1	Schaffhausen	1909	157	1	11	Robiei	1970	410	150
2	Rempen	1925	246	15	12	Ferrera	1971	499	82
3	Tremorgio	1926	920	10	13	Aftendorf	1972	485	53
4	Palü	1941	300	3	14	Hongrin	1972	883	240
5	Oberems	1942	1007	5	15	Handeck III	1974	460	48
6	Peccia	1955	410	21	16	Châtelard	1977	390	70
7	Zervreila	1958	105	6	17	Mapragg	1977	483	161
8	Motec	1959	664	38	18	Sarganserland	1977	449	240
9	Lübbia	1967	730	28	19	Grimsel ll	1979	450	490
10	Ova-Spin	1970	185	47	20	Zermeiggem	1987	445	60

Table 4 : Swiss pumped storage plants. Data from [5, 12]

Swiss storage plants with auxiliary pumping — **Total pump power 241 MW**

N°	Plant	Year	H, m	P, MW	N°	Plant	Year	H, m	P, MW
s1	Cleuson	1953	170	4	s4	Fuhren	1960	184	4
s2	Grimsel	1954	400	19	s5	Tierfehd	1964	542	34
s3	Murteira	1960	196	9	s6	Dixence	1966	300	171

Table 5 : Swiss storage plants with auxiliary pumping. Data from [5]

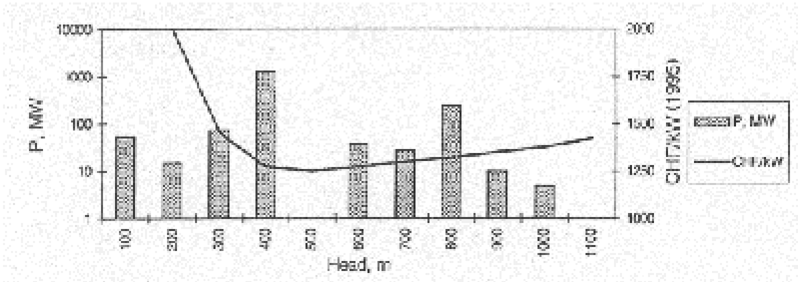


Figure 4 : Pump-mode power and typical unit costs [5) of Swiss pumped storage plants

In 1972, the Swiss Federal bureau for water conservancy drafted a full study of feasible pumped storage power plants [5]. 273 technically feasible sites were screened. Twenty six projects were estimated worthy of a preliminary design study, with pumping mode powers between 200 and 1'200 MW and typically 1'500 hours per year of turbine operation. The economically feasible pumped storage power was found to be 10'000 MW for 324 GWh of storage capacity and 16'349 GWh annually restored from pumped storage.

With the oil crisis of the mid-70s, the conditions for the economical assessment of hydro projects changed. In this respect, the 240 MW Hongrin-Léman (Veytaux) pumped storage scheme is worth special attention. The project initiated in 1963 and operation began in 1970. The scheme consists of 4 Pelton units coupled to 5-stage centrifugal pumps with a 878.2 m gross head, 28.78 km of power tunnel and penstock and a 52 million m^3 storage lake [Forces Motrices Hongrin-Léman S.A. document]. The annual natural water inflow amounts to 190 GWh. Pump-turbine operation was intended as a direct daily tradeoff with the neighboring 284 MW Chavalon oil-fired power plant. The annual power restored from pumped storage was intended to amount to 530 GWh. The raise of oil prices brought a dramatic change to the financial arrangement, but the Hongrin-Léman scheme still turned out to be profitable, even with a reduced pump-mode operation. In 1995, 218 GWh were pumped into the storage lake [8].

As will be discussed below, coming changes in the Swiss electricity market will change again the economical deal, much in favor of pumped storage.

2. Prospects

2.1 Trends in the electricity policy

In the coming years, the Swiss electricity market will change with the liberalization of the European Community electric system. From 1997 to 2003, it will gradually be possible for large consumers (9 GWh annually in 2003) to buy power anywhere on the European grid. The local electric Companies will transport and deliver the energy, charging a reasonable fee for the transmission fines (8).

Even though Switzerland is not properly a member of the European Community, it lies in the middle of the interconnected grid and its exchanges with France and Italy are important. International energy tradeoffs will certainly grow in the future. The Federal policy is to join the European electricity market by 1999.

To meet the European open market with the best assets, the Swiss electric Companies concentrate on two strategies [4, 8]:

- Complete and maintain high capacity, reliable, high voltage transmission lines. One good example is the Galmiz-Verbois 380/220 kV fine under construction.
- Concentrate the production of hydraulic storage power plants on the times of greatest power demand. The most significant example is the upgrade of the Grande Dixence scheme, see 2.2.

The Swiss Federal bureau of water conservancy published in 1996 a prospective synopsis [6] of electric supply for the first half of the next century, based on a 55'000 to 65'000 GWh increase in demand on the National grid. The hydro energy production was assumed to be constant at the 1992 level. Two options were considered for thermal energy production :

- Thermal energy output at the 1992 level;
- Gradual decommissioning of nuclear power plants, suppression of thermal energy for electricity.

The general idea is to import energy at low hours and on weekends and to achieve a financial balance of these imports by exporting peak hour power. This would require 1'700 MW (best case) to 4'500 MW (worst case) of pumps with a storage capacity of 485 to 1'650 GWh. The maximum imported power would reach 6 to 8 GW in low hours.

Five new pumped storage schemes are presently considered [12]. If all five are built, the additional pump power could reach 1'033 MW by 2025. Upgrades of existing pumped storage and seasonal storage power plants could take us a little bit beyond the test case considered in the synopsis, but will not compensate for the decommissioning of Beznau and Mühleberg nuclear power plants.

If the old nuclear power plants are not replaced, Switzerland must seriously consider new pumped storage projects.

Looking back at the 1972 survey discussed in 1.4, the additional pumping power can be achieved, but more storage capacity must be found.

2.2 Optimization and increase of the storage capacity

The change toward a greater modulation of power production requires an increase in the installed power. The energy stored in the mountain dams must be delivered to the electric grid in a shorter number of peak hours. Three upgrade projects of seasonal storage schemes are well advanced, with little or no increase of storage capacity:

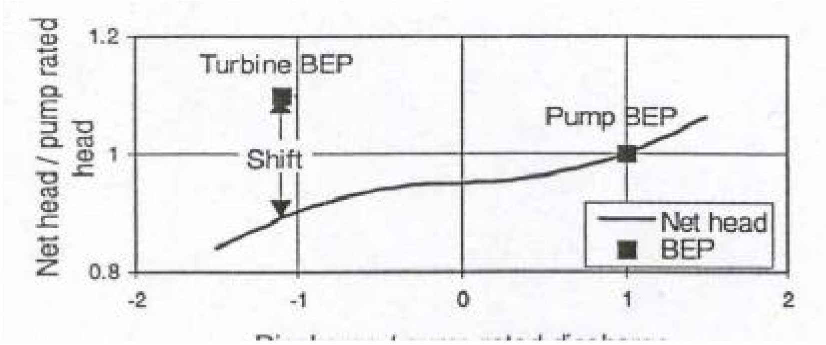
- The Grande Dixence scheme will jump from 870 to 2'070 MW with the new Bieudron power plant, to be commissioned in 1998.
- The Mauvoisin scheme extension from 397 to 900 MW is in project.
- An upgrade of the Grimsel - Oberhasli complex is considered.

The raising of dams can, in some cases, be a very interesting way to increase the seasonal storage capacity if the penstock and surge tank can accommodate the additional head. Works under way on the Luzzone dam and surge tank will raise the lake level by 15 m and increase the storage volume from 87 to 107 million m^3 without modification of the 418 MW powerhouse. This will shift 60 GWh of summer production to the winter months.

2.3. Improvement of pump-turbines with variable speed electric machines

All centrifugal pumps can run as turbines - in fact, normally with higher efficiency thon in pump mode. The problem is that the best efficiency specific energy is greater in turbine mode than in pump mode. With the effect of head losses in the penstock and tunnel, the net head, on the contrary, is smaller in turbine mode thon in pump mode. Pumps have a very pour performance outside of their design conditions, so the project design head and discharge are set as close as possible to the pump best efficiency point (BEP). With the shift in pump and turbine BEPs, the turbine operation of a reversible pump-turbine can be quite bad in terms of efficiency.

A traditional solution to this problem is the use of separate hydraulic machines with switching valves for pump and turbine modes, but this increases the cost of the hydro-mechanical equipment and of the powerhouse. Various innovative ideas were tried to combine separate pump and turbine runners in a single spiral case : Isogyre and Hone machines were eventually built (10], but they are not suitable for high power applications. Multistage pump turbines were built with switchable stages [10], but this again is not very satisfactory. Better results were obtained with two-speed synchronous motor-generators. A two speed electric machine costs 1.3 % more thon a standard one with a power loss of 1.7 % at the lower speed [14].



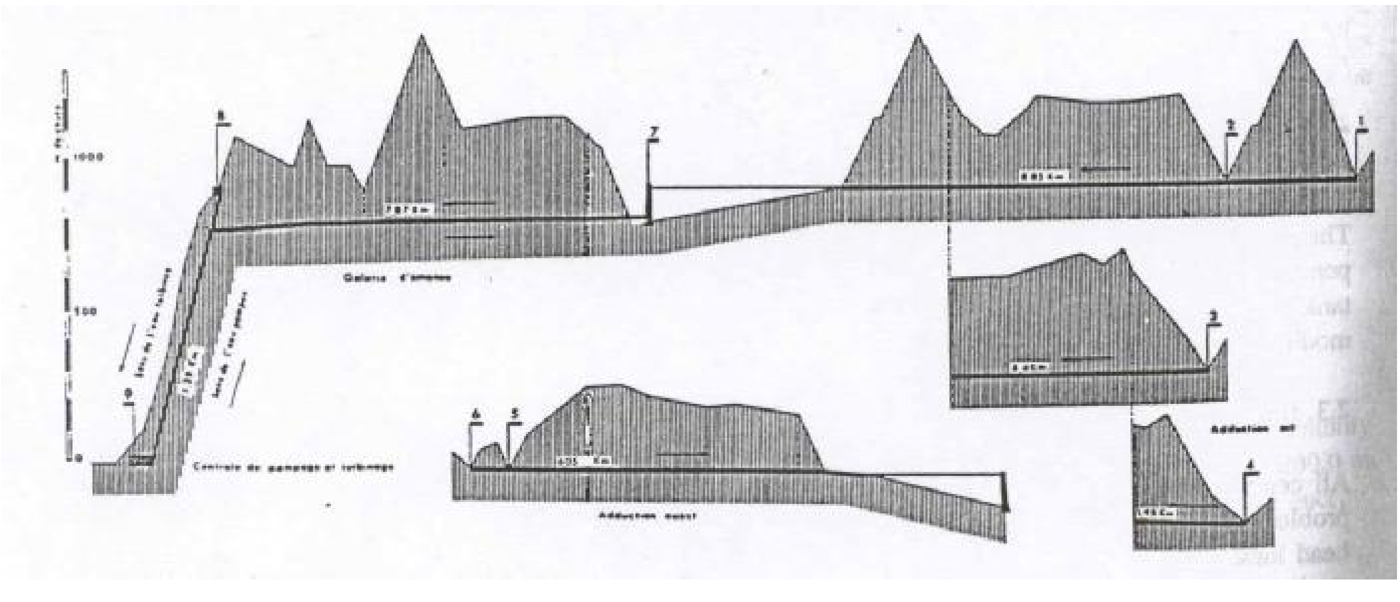
Discharge / pump rated discharge

Figure 5 : Shift in pump and turbine best efficiencies (BEP) of a pump-turbine with regard to net head

Important developments have been done on large power, variable speed motor-generators [1l]. These are mostly synchronous machines excited at variable frequency by a static converter. Two 400 MW pump-turbines with rotational speeds of 330 to 390 rpm were commissioned at Ohkawachi, Japan, in 1993 [13]. Beside solving the best efficiency shift problem, variable speed pump-turbines allow power governing of the electric grid in pump mode. This has a marginal interest in the Swiss case, as small-storage hydro turbine schemes operate all day. Other benefits [l, 2] of variable speed for pump-turbines are:

- A better stability and reduced cavitation at low discharge in pump mode;
- An easier startup in pump mode;
- Power governing of multistage pump-turbines in turbine mode.

A variable speed electric machine costs 4.2 % more than a standard one with a power loss of 1.2 % [14]. There are chances, however, that the variable speed technology could become more efficient and less costly with time.



1 - 6 Auxiliary catchments : 21.25 km of tunnels, catchment area 452 km^2
7 Hongrin dam : crest height 125 m, capacity 52 million m^3, catchment area 45.6 km^2
8 Headwater works for maximum 878.2 m gross head, consisting of power tunnel : 7.87 km, 4.0 m diameter, Sonchaux surge tank and penstock : 1.39 km, 2.9 m diameter
9 Veytaux power plant : 4 horizontal-shaft units, each consisting of 60 MW double runner Pelton turbines, 75 MVA motor - generator and 60 MW, five stage centrifugal pump with diagonal feed pump

Figure 6 : Example of pumped storage scheme (14 in Figure 3) [Forces Motrices Hongrin - Léman]

2.4. Improvement of pump-turbines with modern design techniques

Reversible pump-turbines were traditionally designed as pumps and did as well as they could in turbine operation. Some compromises in design were introduced by rule of thumb. With the development of flow analysis and computer aided design of turbomachines, pump-turbine technology improved remarkably. The notion of the best compromise between pump and turbine operations can be optimized and greater powers are achieved for given machine dimensions [7, 16].

Computer aided design also extends to the mechanical engineering of sensitive parts such as guide vanes and stay vanes, which have been a source of failure due to fluid-structure interaction for some pump-turbines.

Future turbomachine design techniques, in combination with variable speed operation, will result in higher efficiencies, better stability of operation and reduced cavitation damage [2].

Most Swiss pump-turbines were built without computer aided design. Upgrading of these machines would improve the pumped storage possibilities in terms of storable energy, machine reliability and operating restrictions. These improvements would be obtained without modifications of the storage lake, and so without alteration of the Environment.

3. Conclusions

The Swiss geography is ideal for pumped storage power plants. Although there is no excess thermal or run of the river energy in hours of low power demand, pumped storage valorizes the energy produced in summer low hours. Pumped storage could also contribute to the reliability of seasonal storage in case of adverse climate conditions.

Presently, the energy restored from pumped storage is 1'064 GWh per year, i.e. 1.76 % of the electric power production. To preserve the financial balance of electricity exports and imports, this figure should more than double in the first half of the next century. A preliminary design study of 26 new sites showed that 16'349 more GWh could be achieved.

There is an important potential for modernization in the Swiss pumped storage plants.

The author

Dr. Thierry Jacob was educated at the Ecole Polytechnique Fédérale in Lausanne (EPFL). After twelve years in hydraulic turbomachine research at the Institut de Machines Hydrauliques et de Mécanique des Fluides (IMHEF), he joined Stucky Consulting Engineers Ltd. in 1996.

Acknowledgements

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