Operation of hydropower plants without storage by optimizing the turbine flow. Variations to the optimization model

Juan Manuel Blanco Barrero *

Departamento de Energía Eléctrica. E.T.S.I.I., Universidad de La Rioja. San José de Calasanz 31, (Edif. Departam., Dp. 303). Logroño (La Rioja) España
* Corresponding author: juan-manuel.blanco@unirioja.es

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Abstract: Flowing water power plants take advantage of the flows that circulate through the river in which they are implanted. They do not have in their design storage systems that allow the accumulation of river flows for later use. They only have the infrastructures necessary for the conduction of flows and their use. These types of plants are designed and automated to operate between certain flow limits, working with "constant head", using the available flows at any given time. The operating limits are set by the "equipment flow", for which the plant is designed, and the "technical minimum flow", which corresponds to the minimum flow value with which the plant can work, and which depends on each turbine type. This article is a continuation of the research carried out and part of the results of which have been presented in previous congresses. They established the optimization algorithms to take advantage of times of low flow level (dry season) to use the plant's channels as a storage element for flow rates below the technical minimum and to subject the plant to sequential emptying/filling cycles of the same channels, thus allowing energy recovery, which we will call operation by "optimal flow". This article intends to analyze the response of the proposed optimization model to variations in both the design and operation of the power plants in which its implementation is possible. The response of the plant to variations in the usable volume in the channels, the minimum time established for the operation of the plant, as well as the hydrological characteristics of the year of application is presented.

Keywords: Renewable energies, hydroelectric power plants, optimization, regulation.

Introduction

In a hydroelectric power plant, the energy produced is a function, among other parameters, of the volume of water turbined in the power plant. Considering an average yield in the power plant, the energy is determined by:

Volume

$$E = \rho \cdot g \cdot Hn \cdot \eta t \int_T Q \cdot dt$$

$$E = \rho \cdot g \cdot Hn \cdot \eta t \cdot V$$

This Equation determines that, to obtain the maximum energy from the use, the largest volume of water flowing through the river must be turbined.

In the design of the power plants, a flow value is chosen that allows maximum use of the flows to achieve maximum energy use. This flow is chosen by carrying out a hydrological study. In the Flowing Hydroelectric Plants (constant height), a limiting factor in their operation are the turbines, which set the maximum and minimum values of the turbined flows. These flows are limited by the equipment flow (as maximum value) and the technical minimum flow (as minimum flow) which will vary depending on the type of turbine used (Wood *et al*., 2013).

Based on the data on the flows circulating in the river (Figure 1) and the characteristics of the utilization (type of turbine and head), the volumes susceptible to being turbined are determined and the energy generated in the utilization. It is assumed that the entire volume cannot be used for energy purposes, since part of it is lost because it must be allowed to flow through the river as ecological flow and flows above the equipment flow are also not suitable for use in turbines. Nor can flows lower than the technical minimum flow be used (Blanco *et al*., 2007).

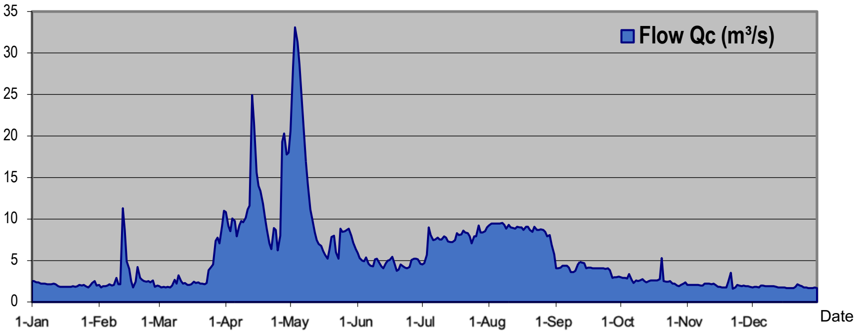

Figure 1. Circulating flows in the Iregua river for an average year (2017). Data source CHE

The strategy for optimizing utilization focuses on the latter flows for their use; flows higher than the equipment flow cannot be used, and the ecological flow must be ensured. Therefore, flows lower than the Technical Minimum are used during low water periods, periods of time during which we would not be able to produce energy under normal conditions, in the figure represented by the Volume Discharged per Technical Minimum.

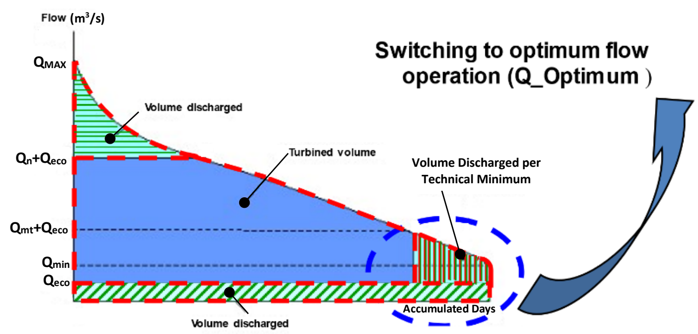

Figure 2. Optimization strategy

In the *optimal flow* operation model, the hydropower plant uses the *accumulation capacity* of its channels to perform a cyclic operation of emptying and filling these channels. The power plant, based on the flows captured from the river and the characteristics of the facility (type of turbine, existing channels and volumes that can be stored in the channel), determines a working flow rate that uses these flows and maximizes energy production (Equation 1).

$$E = V * \eta_{Q_{Out}} * Hn_{Q\_Out} * g * \left(\frac{Q\_Out}{Q\_Out - Q\_In}\right) \quad \textbf{(1)}$$

where E (kWh) is the energy produced when emptying of the channels; V (m^3) is the volumes that can be stored in the channel; $\eta_{(Q\_Out)}$ is the overall performance of the hydropower plant as a function of output flow; $Hn_{(Q\_Out)}$ (m) is the net head of the hydropower plant as a function of the output flow; g (m/s^2) is the acceleration of gravity; Q_In (m^3/s) is the inlet flow into the plant; Q_Out (m^3/s) is the optimal operating flow rate for maximum energy production (Q_Optimunt).

In the *optimum flow* operating mode, the channels of the installation will be periodically filled/empty. To determine the volume to be turbined in the optimum flow operating mode, the most significant restrictions that affect energy production will be taken into account:

- Maximum emptying of the channels.
- Volumes lost due to start-stop of the machine.
- Performance loss due to height loss.

The results of operation at constant head, *optimal flow* and global operation (using the two operating modes together) can be seen in the following table, which shows an increase in energy production of 19.34% for a Francis turbine (this operating mode was presented at the CIDSER 2021 Congress; Blanco J.M., 2021).

Table 1. Comparison of operating modes

	Constant head	Optimal flow	Global operation
Energy Generated (kWh)	3,718,675.60	719,292.63	4,437,968.23
Turbined Days	200	137	337
Annual Equivalent Hours (h)	4,131.86	799.21	4,931.08
Annual Utilization Factor (%)	47.17	9.12	56.29
Turbined Volume (hm^3)	89.11	18.7	107.81
Turbined Volume (%)	52.43	11	63.43

Materials and Methods

A hydropower plant, of the flowing water type, with the following characteristics, is taken as the starting point:

- Concrete channel
  - Cross-section: 2 x 1.5 m^2
  - Length: 1,000 m
  - Volume: 3,000 m^3
- Penstock.
  - Diameter: 1.8 m.
  - Length: 100 m.
  - Material: Steel.
- Gross head of 20 m.
- Losses in pressurised pipelines: 1.2 m.
- Net head: 18.8 m.
- Equipment flow rate (Qn) of 6 m^3/s.
- Average yield: 81.13%.
- Rated power: 900 kW.

To determine the optimum flow rate (Q_Optimun), the performance curves of the electromechanical equipment of the power plant have been modeled (Blanco *et al.*, 2011), obtaining an overall performance curve for each type of use, which will serve as the basis for the study of the various operating flows and for application to the proposed operating model.

For each of the circulating flows that flow through the river (blue function), the following figure (Figure 3) shows the working flows for conventional operation at constant head (green function) and the working flows in an operation with the new algorithms implemented (Equation 1), working with optimum flow (red function).

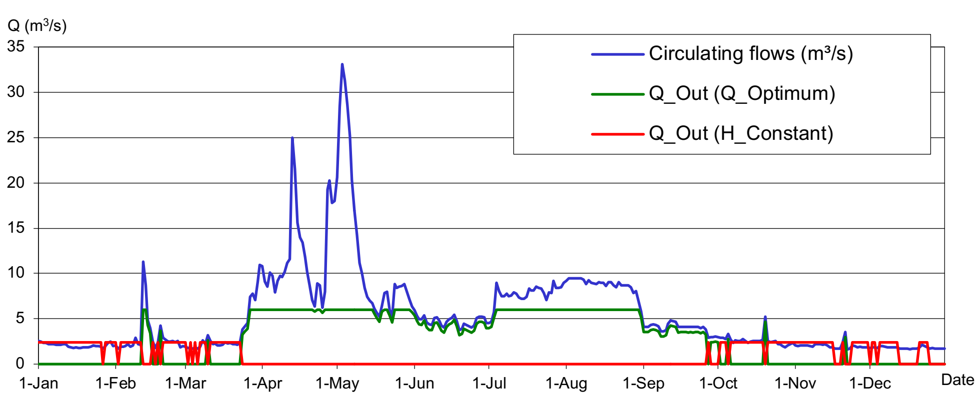

Figure 3. Working flows Q_out

Analyzing the figure above, the plant operates according to the classic model of constant head operation for 200 days, with an annual utilization of 47.17% and an energy production of 3,718,675.60 kWh. The turbined volume is 89.11 hm^3, 52.43% of the total available at the plant.

The operating model proposed at *optimum flow* allows the plant to operate during the days of non-operation in the traditional model, producing an increase in energy production of 719,292.63 kWh, which represents a percentage increase of 19.34% and an increase in annual use of 9.12%. The volume turbined by optimum flow is 18.70 hm^3, 11% of the total volume turbined.

Considering the utilization of the typical hydropower plant according to both modes of operation, the plant works for 337 days throughout the year, with an overall production of 4,437,968.23 kWh, setting its annual utilization at 56.29 %. The increase in turbined volume is 20.98 % with the one used only by constant skip. The annual energy production is represented in the following graph (Figure 4), where the same color code shows the energy generated in the operation mode by constant head (green function) and by optimum flow rate (red function).

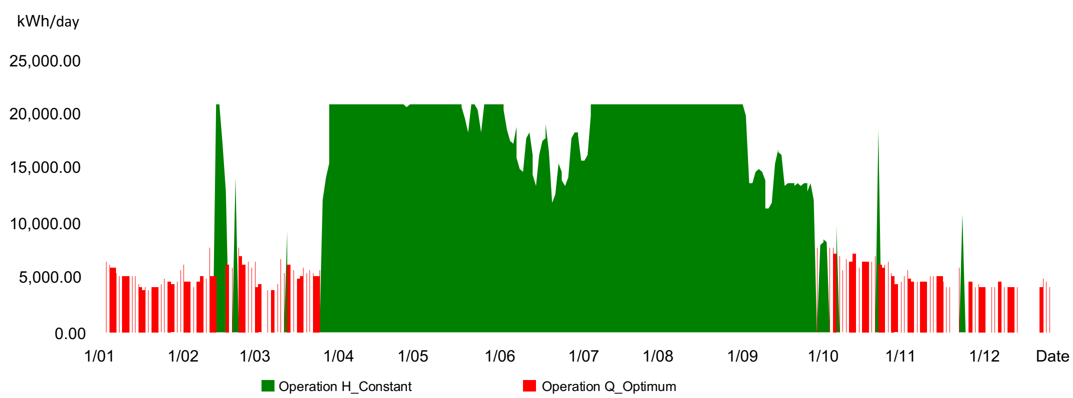

Figure 4. Energy produced for a power plant equipped with a Francis turbine and an accumulation volume of 3,000 m^3

Variation of power plant parameters.

Based on the study of the so-called "typical power plant", several variations of the starting data are analyzed to determine the influence of these variations on the power production of the plant. The influence of:

- The accumulation volume.
- The minimum operating time.
- The hydrological characteristics of the year used.

Results and Discussion

Accumulation volume.

This is one of the fundamental parameters influencing energy production. Initially, a channel volume of 3,000 m^3 has been considered. By analyzing the variation of the model for different storage volumes, the values presented in Table 2 and Figure 5 are obtained.

From the analysis of the data obtained from Table 2 and Figure 5, three zones of unequal influence can be observed depending on the volume accumulated in the pipelines.

Zone V1", for storage volumes up to 2,000 m^3; as the storage volume increases, there are significant increases in the energy production of the plant. In this zone, in operation mode at optimum flow rate, the volume increases directly influence the turbined volumes: as the stored volume increases, the turbined volume increases and therefore the energy production. The plant operates with distributor opening degrees of 40% of the nominal flow rate.

Table 2. Increase in energy production vs. volume of channels

Volume (m³)	∆ Energy (kWh)	∆ Energy (%)
500	54,181.74	1.46
1,000	215,380.67	5.79
1,500	405,737.52	10.91
2,000	640,451.36	17.22
3,000	719,292.63	19.34
4,000	725,884.90	19.52
5,000	729,475.61	19.62
6,000	731,875.24	19.68
7,000	854,119.52	22.97
8,000	855,820.61	23.01
9,000	857,144.70	23.05
10,000	858,204.61	23.08

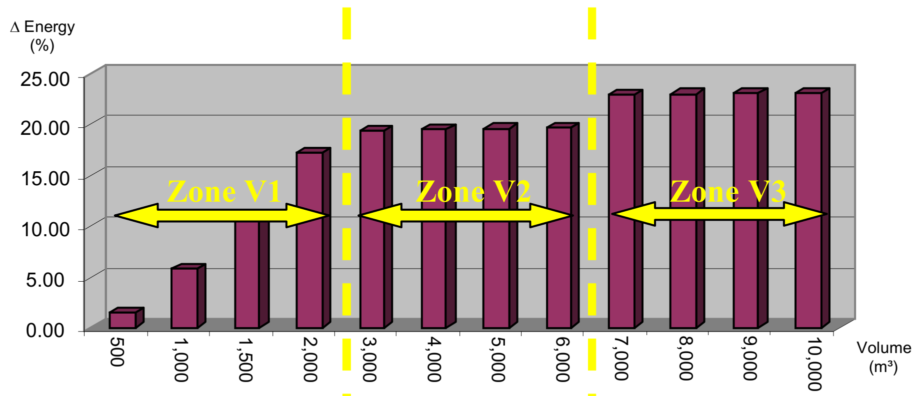

Figure 5. Representation of energy generated vs. accumulation volumes

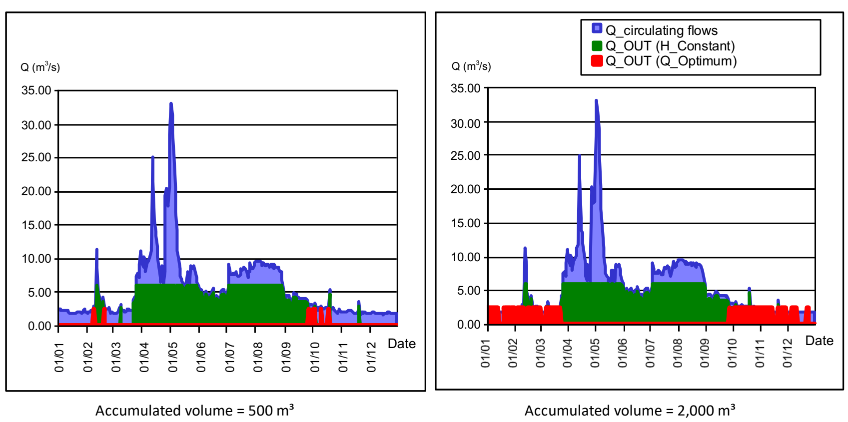

Figure 6. "Zone V1". Comparison of constant head operation vs. optimum flow for 500 and 2,000 m³

For volumes between 3,000 and 6,000 m³ (Zone V2) there are practically no significant variations in production, since for storage volumes in the 3,000 and 6,000 m³ channels, the increase in production is only 0.32%. This is because the plant turbines practically the same volumes. This is due to the fact that the turbine cycles are very long, and this means that the volumes lost in turbine startup and shutdown are very low in comparison with the turbined ones. There are minimal differences between the obtained productions and the turbined volume. The plant works with distributor opening degrees of 40% of the nominal flow (turbine technical minimum limit point).

As can be seen in the comparative graphs in Figure 7, there is no difference between the areas of operation at optimum flow rate.

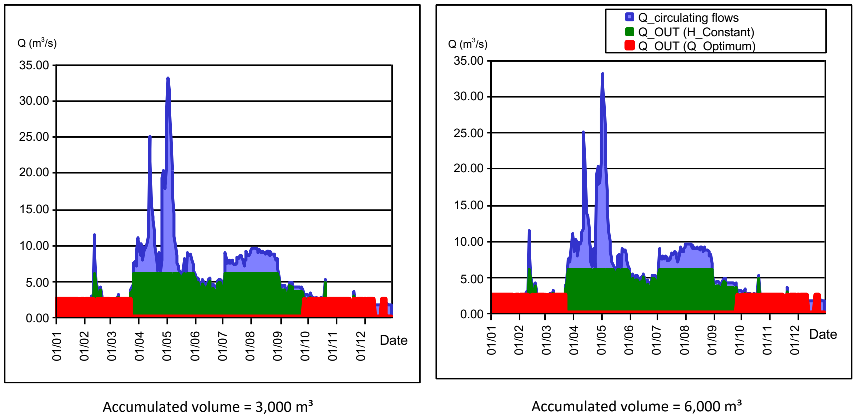

Figure 7. "Zone V2". Comparison of constant head operation vs. optimum flow for 3,000 and 6,000 m^3

For storage volumes greater than 6,000 m³, a significant increase is observed from 6,000 to 7,000 m³, with energy increases being maintained thereafter (Zone V3). For storage volumes in channels of 7,000 m³ or higher, the power plant works with opening degrees around 85% of the nominal flow (optimum point of turbine efficiency), producing higher yields and therefore higher energy yields when emptying the channels.

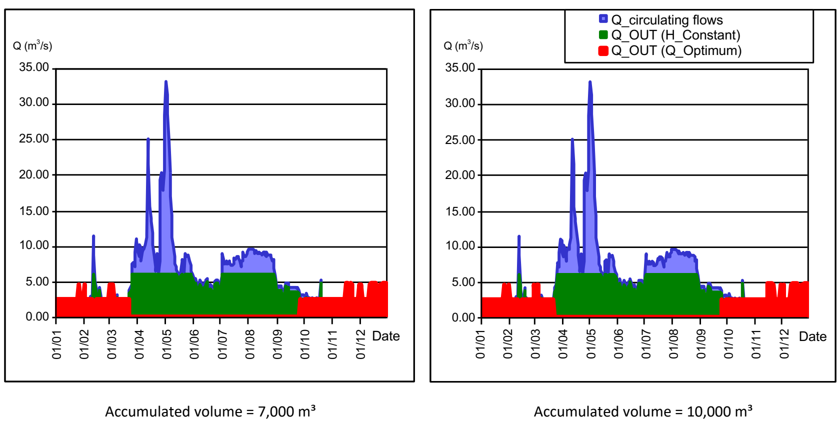

Figure 8. "Zone V3". Comparison of constant head vs. optimum flow for 7,000 and 10,000 m^3

Minimum operating time.

Another limitation in terms of the operation of the power plant is the minimum operating time for emptying the channels that we set in the plant. This time a priori has as only limitation the one corresponding to the fastest emptying of the channels.

For the 3,000 m³ of accumulation, with an opening degree of the distributor of 87.09% in operation at optimum flow, a minimum emptying time of 0.20 hours is obtained $t=f(Q\_OUT, T_{Connection})$; (Blanco J.M., 2021). From this value (absolute minimum operating time), the analysis of behavior and energy production for longer minimum operating times is carried out, not allowing the plant to operate for values lower than the preset value.

The analysis is performed from 0.2 hours to 21 hours, since from then on the plant cannot work at optimum flow rate, since it is more efficient to work in constant skip mode.

Table 3. Variation Energy generated vs. minimum allowable channels emptying time

Minimum time	∆ Energy (kWh)	∆ Energy (%)	Days	Minimum time	∆ Energy (kWh)	∆ Energy (%)	Days
0.20	836,064.78	22.48	165	3.00	60,295.26	1.62	8
0.30	719,292.63	19.36	137	3.50	53,278.42	1.43	7
0.40	719,292.63	19.36	137	4.00	46,050.00	1.24	6
0.50	719,292.63	19.36	137	5.00	38,751.32	1.04	5
0.60	719,292.63	19.36	137	6.00	38,751.32	1.04	5
0.70	719,292.63	19.36	137	7.00	38,751.32	1.04	5
0.80	578,703.83	15.56	103	8.00	38,751.32	1.04	5
0.90	462,864.72	12.45	78	9.00	38,751.32	1.04	5
1.00	418,402.53	11.25	69	10.0	38,751.32	1.04	5
1.10	313,500.75	8.43	49	11.00	23,366.52	0.63	3
1.20	297,224.20	7.99	46	12.00	15,638.02	0.42	2
1.30	268,916.88	7.23	41	13.00	15,638.02	0.42	2
1.40	245,552.42	6.60	37	14.00	15,638.02	0.42	2
1.50	227,598.81	6.12	34	15.00	15,638.02	0.42	2
1.60	215,460.44	5.79	32	16.00	15,638.02	0.42	2
1.70	190,639.99	5.13	28	17.00	7,837.15	0.21	1
1.80	171,803.02	4.62	25	18.00	7,837.15	0.21	1
1.90	139,803.63	3.76	20	19.00	7,837.15	0.21	1
2.00	120,384.38	3.24	17	20.00	7,837.15	0.21	1
2.50	74,118.96	1.99	10	21.00	0.00	0.00	0

From the analysis of the data (Table 3) and its representation (Figure 9) we can observe three well differentiated areas of operation.

“Zone T1”, for minimum time values up to 0.2 hours, where both the number of operating days per optimum flow rate (165) and the increase in energy generated remain constant. From this zone it is only possible to use the plant with a minimum time of 0.2 hours since this is the shortest time for emptying the channels. Moreover, in terms of utilization, this time is not feasible, since it can only occur for distributor openings of 87.09% and is not efficient for all flow ranges, since it will only be efficient for flows below 5% of the nominal flow and does not occur during the 165 days.

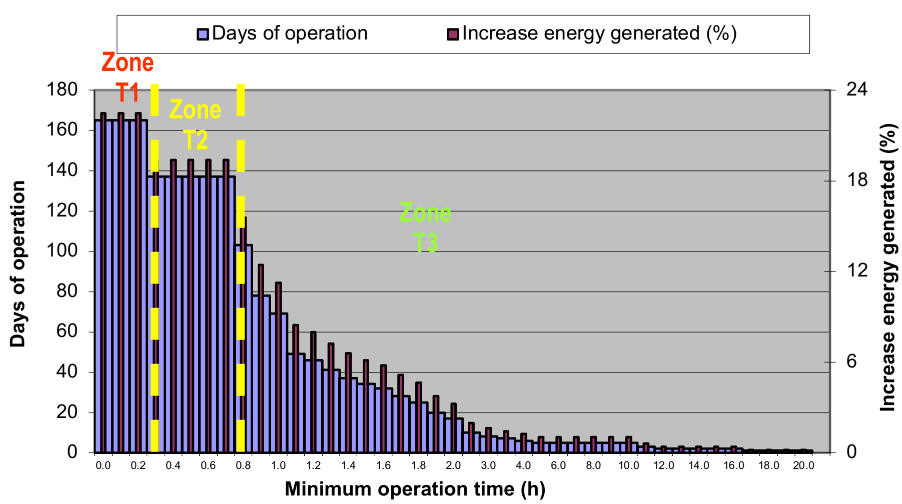

Figure 9. Representation of increase in energy generated and days of operation vs. minimum operating time

"Zone T2" for time values from 0.3 to 0.7 hours. In this zone, the number of days turbined per optimum flow rate (137) and the increase in energy produced in these days are also kept constant. Any of the time values is feasible both technically and efficiently, preferring the use of the highest value (0.7 hours), which implies a lower number of maneuvers in the plant.

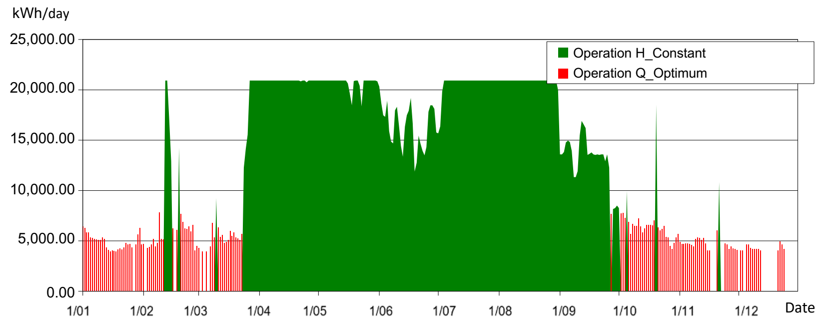

Figure 10. Energy produced for a minimum time of 0.7 hours (Zone T2)

Zone T3" where, as the minimum operating time increases, the number of days to be turbined is reduced and the increase in energy generated is also reduced. As the minimum operating time increases, the minimum flow to be withdrawn to allow the power plant to operate also increases.

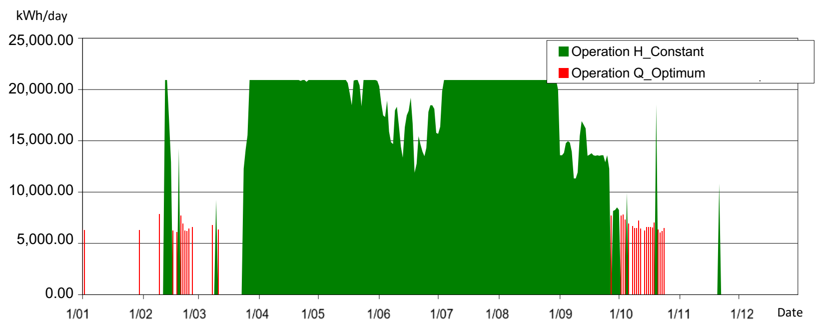

Figure 11. Energy produced for a minimum time of 1.5 hours (Zone T3)

Joint variation Volume/Minimum time

Representing the joint variation of the parameters, accumulation volume and minimum operating time (Figure 12), for the different accumulation volumes proposed, the operating zones obtained by varying the minimum operating time are maintained.

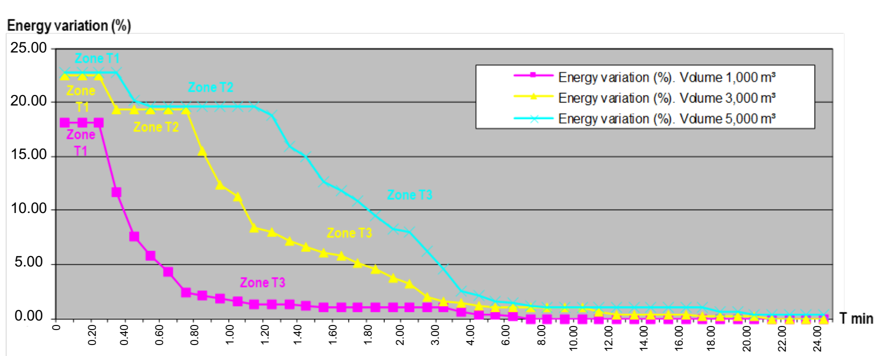

Figure 12. Variation of % of energy generated vs. minimum operating time for different storage volumes

The larger the accumulation volume, the larger the minimum time operating zones. If the storage volume is reduced, the zones are reduced. In the case of an accumulation volume of 1,000 m³, Zone T2 disappears, moving from minimum operations with stable production (Zone T1) to the zone of decreasing energy variations, depending on time variations (Zone T3).

The larger the storage volume, the higher the yields, the shorter the downtimes and the larger the stable operating areas of the power plant.

Variation in the characteristics of the year

The tests performed so far have been carried out for a hydrological year obtained from the 40-year series, considered as an average year.

The variations in the operation of the plant are compared according to the optimal flow operation model for other types of dry and wet years.

According to the hydrological study carried out on the flow data and choosing years close in time, the study years are chosen:

- Year 2014. Wet year.
- Year 2016, Dry year.

In 2014 it has an annual contribution of 225.67 hm³, with an average flow of 7.16 m³/s. In 2016 its contribution is 140.67 hm³ and it has an average flow of 4.46 m³/s.

Table 4. Operation by "constant heat"

Year	Volume (Hm³)	Energy (kWh)	Turbined days	Turbined days (%)	Turbined Volume (Hm³)	Turbined Volume (%)	Annual operation (h)	Annual operation (%)
2014	225.67	5,191,556.03	272.00	74.52	125.73	55.71	5,191.56	59.26
2017	169.97	3,718,675.60	200.00	54.79	89.11	52.43	3,718.68	42.45
2016	140.67	3,722,773.24	214.00	58.63	87.52	62.22	3,722.77	42.50

Table 5. Operation by "optimal flow"

Year	Energy (kWh)	Days turbined	∆ Days turbined	Turbined Volume (Hm³)	Turbined Volume (%)	Annual operation (h)	Annual operation (%)
2014	528,082.51	93.00	25.48	13.68	6.06	528.08	6.03
2017	719,292.63	137.00	37.53	18.70	11.00	719.29	8.21
2016	837,380.03	151.00	41.37	21.73	15.45	837.38	9.56

Table 6. Global operation

Year	Energy (kWh)	∆ Energy (%)	Turbined days	Turbined days (%)	Turbined Volume (Hm³)	Turbined Volume (%)	Annual operation (h)	Annual operation (%)
2014	5,719,638.54	10.17	365.00	100.00	139.41	61.78	5,719.64	65.29
2017	4,437,968.23	19.34	337.00	92.33	107.81	63.43	4,437.97	50.66
2016	4,560,153.27	22.49	365.00	100.00	109.25	77.66	4,560.15	52.06

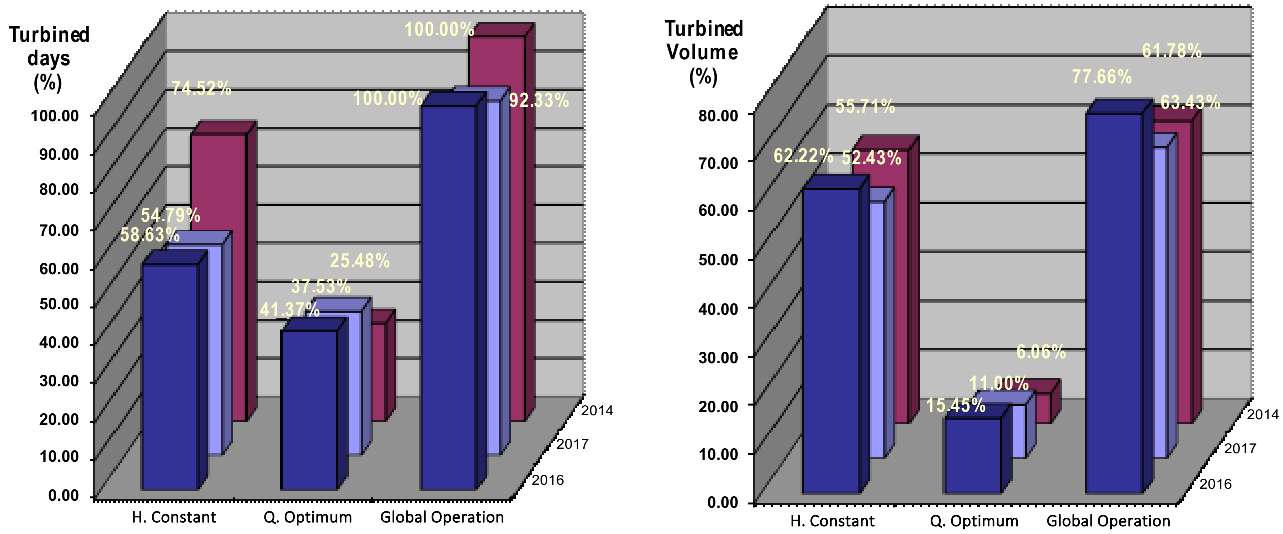

Figure 13. Comparison of years in % of days and volumes turbined by the plant for each model (Francis Penstock)

Applying the new flow rates to the models, the results shown in the Tables 4 to 6 and the graphs in Figure 13 are obtained. In each section you can see the tables of results for the traditional exploitation model at constant head, the exploitation model proposed at optimum flow and the combined use of the models.

In dry years, the power plant optimizes its operation by optimum flow rate, since the operating period during which it can work is longer and the energy produced by the plant is also higher.

In wet years, by extending the period of operation by constant head, the operation of the optimal flow operation model is reduced and the energy produced by this method. These data lead us to affirm that the plant works better in the optimal flow operation model the drier the year is.

Conclusions

For the optimal flow optimization model, for the type of power plant analyzed, an increase in energy production of 19.34% is obtained, which results in the equivalent hours of annual use and in the profitability of the plant.

From the tests carried out in the application of the optimal flow exploitation model in the face of variations in the accumulation volume of the channels, the general conclusion can be drawn that the greater the accumulation volume, the greater the energy generated. This increase in production can be divided into three zones of different energy variations in relation to the accumulation volume.

For low storage volumes, the higher the available volume, the higher the growth in energy produced. For intermediate storage volumes, there are small variations in production, which remains practically constant. For high storage volumes, there is an increase in the energy produced with respect to the lower volumes, but it remains very constant for all the volumes tested.

About the influence of the minimum emptying time, three zones of operation are obtained. The zone of minimum time values (up to 0.2 hours), where both the number of days of operation per optimum flow and the increase in energy generated remain constant and where the model proposed does not apply. The zone of times between 0.3 and 0.7 hours, where the number of days turbined by optimum flow and the increase in energy produced in these days are kept constant. Any of the time values is feasible both technically and efficiently, preferring the use of the highest value (0.7 hours), which implies a lower number of maneuvers in the plant and optimizes its operation. The zone of minimum times greater than 0.7 hours, as the minimum operating time increases, the number of days to be turbined and the increase in energy generated are reduced.

Analyzing the performance of the model for different types of years, medium, dry, or wet, the result is that in dry years the plant optimizes its operation better due to optimum flow and the energy produced is higher.

In wet years, by extending the period of operation by constant head, the operation of the optimal flow operation model is reduced, and the energy produced by this method is also reduced.

The application of the *optimal flow* exploitation model favors obtaining a more constant energy production throughout the different types of years, since the years in which more production is obtained by the constant head exploitation model, less production is obtained by optimal flow, and conversely, for years with low production by the constant head model, more production is obtained by the *optimal flow* exploitation model.

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