SimTerm 2019

Energy – Efficiency – Ecology

PROCEEDINGS

19th International Conference on
Thermal Science and Engineering of Serbia

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October 22-25
2019

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Managing the turbine discharges of hydro cascade power system in electricity market environment

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Abstract: The paper gives the methodology for water managing in hydro energy system consists of infrastructure pipes and/or channels (for run off and turbine inflow), power plants facilities (turbine and generator), reservoirs which are all hydraulically connected. The goal of water discharge is to have maximum profit from electricity production taking into account electricity market prices as well as satisfying technical conditions and avoiding water spilling as it is maximum possible. Operating mode of the hydro power plants depend on electricity market price, tariff prices and time duration of each tariff (base, peak, and others), technical characteristics of the unit(s), hydro technical conditions, water reservoir's volumes, run off and others.

Keywords: Hydro energy system, hydro power plant, generation, electricity, water, turbine discharge.

1. Introduction

The application of the model on the hydro energy system on river Crn Drim can give directions for operating the hydro power plants in the hydro energy system. The hydro energy system of river Crn Drim consists of 2 hydro power plants (HPP Globocica 2x21 MW and full turbine discharge of 50 m^3/s) and HPP Spilje (3x28MW and full turbine discharge of 108 m^3/s), three reservoirs (Ohrid lake, Reservoir of Globocica and Debar lake) and main run off from two rivers (Crn Drim and Radika).

The purpose of the research is to have preliminary analysis for additional installed power of the system, so the model is implemented on the existing hydro energy system and on the projection one with additional installed units. The analysis are done on real data taken from the database of water inflow of 50 years historical period with representative year of dry, average and wet hydrological condition. The selected outputs of the results is presented with appropriated comparing and at the end with conclusion remarks.

2. Basic information

The contribution of the Hydro Power System (HPS) of Crn Drim in electricity generation in the share of hydroelectric power plants in Macedonia is about 35%. The two power plants Globocica and Spilje contribute on average with 450-500 GWh of generated electricity in the power system of Macedonia. HPP Globocica as the first upper stream power plant in HPS Crn Drim is a derivative power plant that uses the accumulation of Lake Ohrid, where through the reservoir of Globocica the turbine flow in the two turbines is released. The installation of each of the two units is 25 m^3/s or total of 50 m^3/s, with a total installed capacity of 42 MW, and gross head of 108-110 m. The turbine flow from HPP Globocica and the Radika River are the main run offs for Debar Lake as the reservoir of HPP Spilje. HPP Spilje has 3 units, each of 36 m^3/s or total of 108 $m^3/$ s, with gross head of 80-100 m, and total installed capacity of 84 MW.

Figure 1 schematically presents the existing HPS of Crn Drim with both planned additional units in new HPP Globocica and existing HPP Spilje. The additional unit in new HPP Globocica has 20 m^3/s turbine flow and 12 MW installed power located in new turbine hall with 70 m gross head. The additional unit in HPP Spilje has 36 m^3/s turbine flow and 28 MW installed power the same as the existing ones and located in the same turbine hall [1]. The others basic technical parameters [2] as the reservoirs' volumes, attitudes of the turbines, minimum and maximum reservoir levels, turbine flows and installed power are given on the Figure 1. The allowed surface elevation for Ohrid Lake is between 693,3 asl and 693,75 asl, for Globocica Lake is between 683 asl and 687 asl and for Debar Lake is between 561 asl and 580 asl.

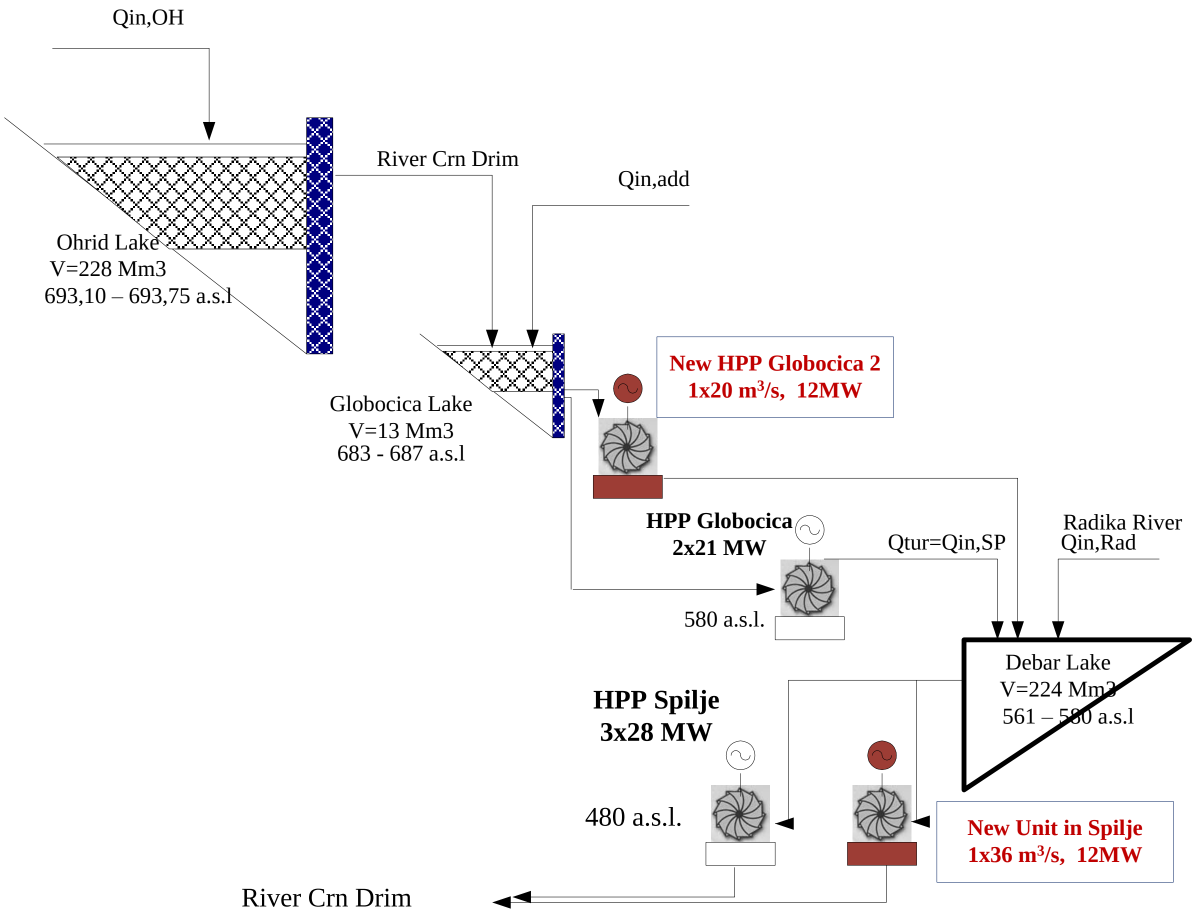


Figure 1. Scheme of the HPS Crn Drim

The main idea of the simulation is to find the operational regimes with maximum financial benefit under new market conditions with electricity prices on the open market in different tariffs. Taking into account the existing operational experiences of the HPS Crn Drim, it is taken 2 tariffs: base load tariff in 24 hours in a day (00-24), and peak load tariff for 12 hours in a day (08-20).

The water inflow for HPP Globocica ($Q_{in,GL}$) is predominantly from Lake of Ohrid ($Q_{in,OH}$), and the additional run offs ($Q_{in,add}$):

$$Q_{in,GL}(t) = Q_{in,OH}(t) + Q_{in,add}(t) \tag{1}$$

The water inflow for HPP Spilje ($Q_{in,SP}$) mainly depends on the turbine flow of HPP Globocica ($Q_{tur,GL}$) and the natural run off from Radika River ($Q_{in,Rad}$):

$$Q_{in,SP}(t) = Q_{tur,GL}(t) + Q_{in,Rad}(t) \tag{2}$$

3. Simulation of the operation modes for HPS Crn Drim

The simulation of the hydro power plants operation, Globocica and Spilje as the generating facilities in HPS of Crn Drim, has made in two variants:

• Existing state of installation of both power plants

• Operation of the existing HPS with additional HPP Globocica 2 with one unit of 20 m^3/s and gross head of 70 m, and with the fourth additional unit of 36 m^3/s in the same turbine hall of the existing HPP Spilje.

According to natural flows from the input hydrological data [2], three characteristic hydrological years have been selected:

- Dry Year - Representative 2001
- Average year - representative 2006
- Wet Year - Representative 2013

Table 1 shows the monthly water inflows for the reservoirs in HPP Globocica and HPP Spilje in each of the representative year.

Table 1. Monthly water inflows for the Reservoirs of the both HPPs for the three representative year

	Water inflow for Reservoir of Globocica						Water inflow for Reserv.of Spilje		
	2001 dry hydrology		2006 aver. hydrology		2013 wet hydrology		2001	2006	2013
month	Qin,OH	Qin,add	Qin,OH	Qin,add	Qin,OH	Qin,add	Qin,Rad	Qin,Rad	Qin,Rad
1	14,15	4,30	25,76	9,29	34,26	11,85	10,34	25,81	21,33
2	16,92	5,16	26,90	7,04	42,87	12,42	12,12	23,44	23,16
3	22,05	10,39	50,71	18,23	61,96	19,20	27,86	44,64	56,77
4	24,97	7,71	51,69	23,42	47,35	31,67	28,52	84,44	114,32
5	13,34	7,25	25,86	14,65	34,56	22,16	25,51	66,92	90,34
6	6,86	4,36	13,94	10,47	10,54	12,46	10,82	26,81	33,52
7	-0,08	2,53	8,62	4,13	5,61	4,78	5,48	14,82	16,12
8	0,27	1,75	4,35	2,52	1,96	1,32	2,59	12,33	9,42
9	-1,88	2,23	6,76	1,93	5,78	0,22	4,99	7,64	8,85
10	-2,48	2,00	9,66	2,73	19,12	0,14	4,46	6,22	9,65
11	1,61	1,20	10,22	3,70	18,51	2,45	7,23	6,71	9,38
12	6,32	1,44	7,92	4,31	12,42	-0,82	5,92	7,39	10,40
Average	8,50	4,19	20,20	8,54	24,58	9,82	12,15	27,26	33,60

3.1. Modeling the water reservoirs

In order to simulate the operation regimes of the whole system, it is necessary to know the characteristics of the reservoirs of Lake Ohrid and of Debar Lake. The small reservoir of Globocica can be taken as daily one in long-term analyzes (seasonal, annual and multi-year). Modeling of the characteristic of the both reservoirs is done according [3] as two functions, volume dependence of the attitude (3) and vice versa, the attitude dependence of the volume (4) according [3].

$$Vol(Att) = 2 \cdot \pi \cdot (A + B \cdot Att + C \cdot Att^2) \tag{3}$$

$$Att(Vol) = g + h \cdot (Vol - d)^e \tag{4}$$

The parameters in the formulas (3) and (4) for both reservoirs are given in Tab.2.

Table 2. The parameters for both reservoirs in (3) and (4).

Reservoir	A	B	C	g	d	h	e
Ohrid	1639724,298	-4862,698475	3,602532579	674,900	-3136,00	0,325	0,5
Debar	5790,194	-23,50359	0,023551	498,993	-194,14	4,02	0,5

3.2. Conditions for operating regimes in simulations

The simulations of the operating regimes has been done taking into account the characteristics of the reservoirs, the water inflows and the turbine characteristics of the two hydropower plants [4]. The following input data from [2] was taken:

- Average monthly inflows for the Globocica reservoir, a stream from Lake Ohrid and additional inflow
- Average monthly run offs from Radika river as the inflows for Debar lake
- The characteristic of the electric power output P=f (Q_{tur}, H_{att}), as a function of turbine flow (Q_{tur}) and attitude level (H_{att}) of the water reservoir
- The characteristics of the two reservoirs according (3) and (4)
- Average electricity prices from the 2018 (on a monthly basis)

The simulations are made on the monthly level for each time interval in the whole period. The following conditions and assumptions are taking into accounts:

- The reservoirs level to be within the permitted limits and avoiding spilling.

- The turbine flow priority is according to the electricity market prices for each period of the day in order to have maximum revenue from generated electricity.

The output from the calculations are the following ones:

- Consumed water volume in each time period (month) for each reservoir
- Output power for each period of the day
- Electricity generated for each period of the day
- Financial profit from the sold electricity in each month and total

The time periods for each day are divided into 2 groups (tariffs) given in Tab.3, and the simulations were done according to the average monthly price of the electricity market for 2018.

- Base tariff (C_{base}) with duration of 24 hours for the period 00-24.
- Peak tariff (C_{peak}) with duration of 12 hours for the period 08-20.

Table 3. Daily tariffs and electricity price C(€ / MWh)

Month	C_{base} (00-24) (€/MWh)	C_{peak} (08-20) (€/MWh)
1	35,42	43,57
2	41,65	47,90
3	40,43	46,60
4	31,92	33,04
5	42,17	46,32
6	51,27	57,38
7	50,95	53,85
8	60,45	65,12
9	62,94	70,25
10	64,49	74,38
11	63,65	73,54
12	65,07	74,74

The simulations are made for two cases:

• Case of existing installation of the HPS Crn Drim, HPP Globocica with two units 2x25=50 m^3/s, and HPP Spilje with three units 3x36 = 108 m^3/s

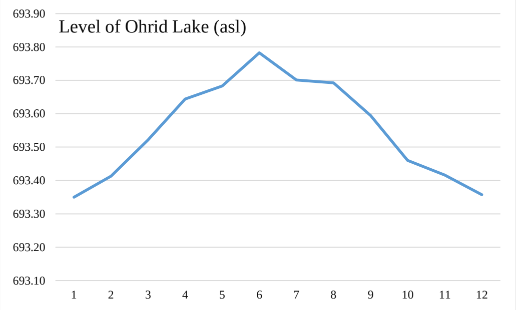
• Case of existing installation with new HPP Globocica 2 with one unit 1x20 = 20 m^3/s and gross head of 70m, and an additional unit in HPP Spilje same as the existing ones, 1x36 = 36 m^3/s.

4. Results from the simulations

The starting value of the reservoirs level in 1st of January is common for all simulations, for Ohrid Lake is 693.3 a.s.l., and for Debar Lake is 563 a.s.l. The consumed water of both cases is the same for dry, average or wet year. This is important for comparing operating modes, electricity produced and financial revenue for both cases, without and with the additional units. The additional units operate in peak tariff for all cases.

4.1. Case with additional units in wet year

The simulations are made for three years, dry 2001, average 2006 and wet 2013, and for case as existing HPS and the case with additional units. The results for the representative of wet year 2013 in a case of the system with additional units is presented in this chapter. Fig2 and Fig.3 present the level of the reservoirs and the spent volume of water for HPP Globocica (dV_GL) and HPP Spilje (dV_SP) respectively.



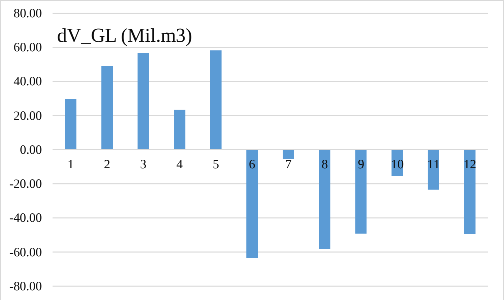
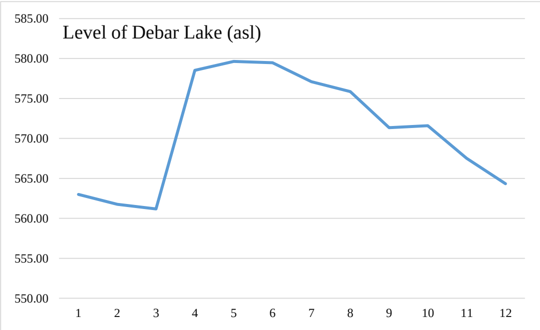


Figure 2. Reservoir level of Ohrid Lake and spent volume of water in HPP Globocica for each month in wet 2013



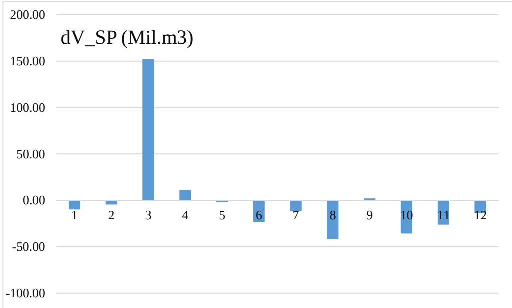


Figure 3. Reservoir level of Debar Lake and spent volume of water in HPP Spilje for each month in wet 2013

Considering the hydraulic connection between the two HPPs and the reservoirs, the operation of HPP Globocica is with 3 units with total turbine flow of 50+20=70 m^3/s and HPP Spilje is with 4 units with total turbine flow of 108+36=144 m^3/s. In order to avoid overflowing and spilling, the maximum installed turbine flow for both HPPs is in the first months, and the case with an additional units the spilling is reduced and it is only in April.

The total balance of the both HPPs in the HPS of Crn Drim in generated electricity and financial income from the sold electricity is given in Table 4.

Table 4. Generated electricity and financial income for the wet 2013 in case with additional units in HPS Crn Drim

	Generated Electricity (MWh)				Financial Income (Euro)			
	Wbase	Wpeak	Wspill	Wnew,peak	FINbase	FINpeak	FINspill	FINnew,peak
1	0	39717	0	9153	0	1730564	0	398824
2	0	35525	0	8198	0	1701665	0	392673
3	31329	23489	0	9040	1266592	1094496	0	421252
4	90595	36202	-36202	14249	2892173	1196258	-1196258	470834
5	63037	15665	0	14849	2658123	725661	0	687868
6	35456	27876	0	14351	1817897	1599635	0	823503
7	0	26575	0	0	0	1431031	0	0
8	0	43686	0	0	0	2844794	0	0
9	0	32167	0	0	0	2259591	0	0
10	0	33289	0	8011	0	2476192	0	595900
11	0	31409	0	10226	0	2309890	0	752047
12	0	31811	0	8287	0	2377635	0	619418
SUM	220417	377410	-36202	96364	8634785	21747413	-1196258	5162319
Total				657990				34348258

The total generated electricity consists of 4 parts, 3 parts are base, peak, new units in peak, where the income comes from, and the forth part is lost electricity because spilling. Therefore, for wet 2013, the all hydro power plants with additional units of HPS Crn Drim gives:

• Production of around 658 GWh with total electricity sales of approximately 34.3 million euros.

• Overflow of about 36 GWh with a total loss of un-produced electricity of about 1.2 million euros.

Fig.4 gives graphical presentation of the generated electricity and the income from produced electricity in each month for the whole HPS Crn Drim in the wet 2013. The lost electricity and appropriated lost income are negative (bellow the apices axis in month of April). .

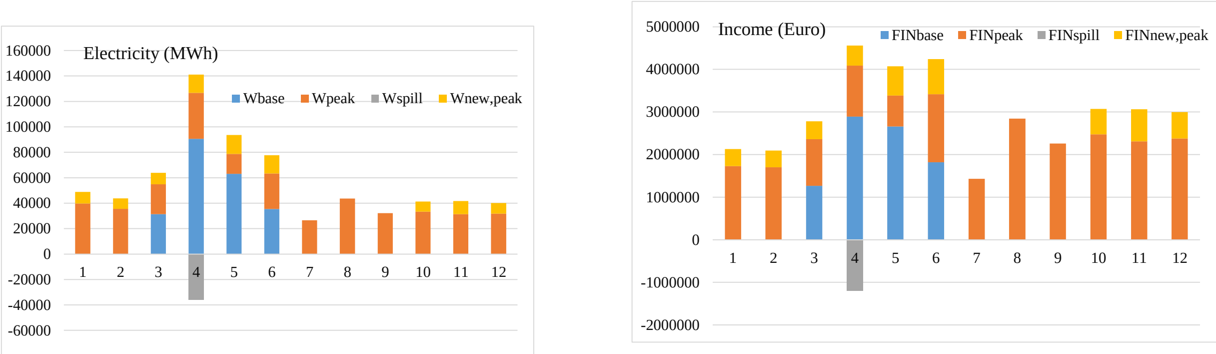


Figure 4. Monthly production and income for the HPS Crn Drim in wet 2013

4.2. Comparing the all operating regimes

According the calculation for all cases and for all representative years, the comparison of the results can be analyzed in order to have answer for the benefit of additional units installed of the HPS Crn Drim, which is very useful for further additional techno-economic analyzes. Tab.5 and Fig.5 show the generated electricity and lost energy in spilling, for all representative years. The year 2001 was considered only with the existing installation because there is no engagement of the additional units. For the years 2006 (average) and 2013 (wet) are given the results for both cases, with existing and with new units (exist.+new). The difference between the calculations of the new and the existing stage is given in the last two columns.

Table 5. Generated electricity and spilled energy in MWh for all cases for HPS Crn Drim

	Dry 2001 exist.	Aver. 2006 exist.	Aver. 2006 exist.+new	Wet 2013 exist.	Wet 2013 exist.+new	2006 New-Exis	2013 New-Exis
Wbase	0	267294	88440	298216	220417	-178855	-77799
Wpeak	194431	321781	409312	409120	377410	87531	-31710
Wspill	0	0	0	-85488	-36202	0	49287
Wnew,peak	0	0	89148	0	96364	89148	96364
TOTAL	194431	589075	586900	621848	657990	-2176	36142

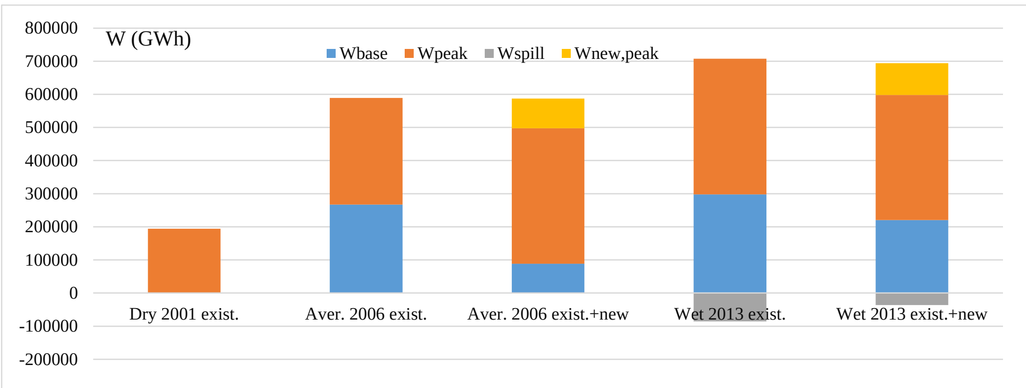


Figure 5. Comparing the output energy for all cases

The results show that the cases with new additional units reduce the electricity production in base tariff W_{base}, comparing with cases in existing stage of the HPS Crn Drim. On the other side, the increased production can be got in additional and existing units in peak tariffs with high prices. The other benefit of additional units is reducing the lost energy of spilling in wet 2013 from 85488 MWh to 36202 MWh, and the difference goes to additional peak electricity of the system.

Tab.6 and Fig.6 give the benefit in Euro from income of generated electricity taking into account the lost energy of spilling.

Table 6. Financial benefit from income in Euro for all cases for HPS Crn Drim

	Dry 2001 exist.	Aver. 2006 exist.	Aver. 2006 exist.+new	Wet 2013 exist.	Wet 2013 exist.+new	2006 New-Exis	2013 New-Exis
Wbase	0	11153509	3866861	12183321	8634785	-7286648	-3548536
Wpeak	10785275	19678486	23357799	23441209	21747413	3679313	-1693795
Wspill	0	0	0	-3309868	-1196258	0	2113610
Wnew,peak	0	0	4771037	0	5162319	4771037	5162319
TOTAL	10785275	30831995	31995696	32314661	34348258	1163701	2033597

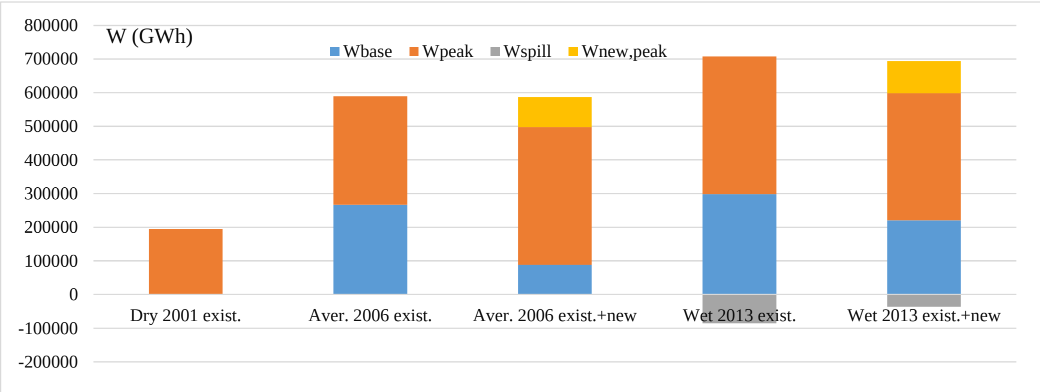


Figure 6. Comparing the income for all cases

The last two columns in Tab.6 give the benefit for additional units installed in the existing system for all tariffs and periods (base, peak, new unit and spill energy). The overall benefit for average 2006 is approximately 1,16 Mil.Euro and for the wet 2013 is approximately 2,03 Mil.Euro.

4. Conclusion remarks

The operating mode of the system depends on the installation of HPP Globocica and HPP Spilje (existing without / with new units) and electricity prices. In case of low price differences between high and low tariffs (base and peak ones), there is no financial benefit from forcing the HPP Globocica 2 in high tariff, except in periods to avoid overflow. Forcing the operation of new unit in HPP Globocica 2 in peak high tariff would be financially acceptable when $C_{peak}/C_{base} > 102m/70m = 1,43$ or when the peak energy is higher by 43% of the base energy. In such a price-to-base ratio, financial equity and suitability for discharging the water through the additional unit will be obtained. HPP Spilje with additional fourth unit could operate in high tariff periods as well as other existing 3 aggregates.

The benefits of an additional unit in HPP Globocica 2 and a fourth unit in HPP Spilje should be valorized in generated electricity as well as financial benefit for the entire system, such as:

- Higher electricity production as a result of utilization of the overflow spilling water of Crn Drim.
- Engagement of the units in periods of high tariffs per day, rather than production as a base plant.
- Opportunity for optimization of the whole system of HPS Crn Drim,
- Optimizing the hydropower system and avoid overflows, in order to obtain positive financial effects from the operation the entire hydro system of Crn Drim.
- Possibility for regulating the flow of Crn Drim, as well as regulation of the Ohrid Lake.

The methodology for operation modes of hydro power plants presented in the paper can be applied in different needs depend on input data and the requirements from the utility or operator of the power plant. Some of the possible application can be done for:

- Different time period of consideration (T) as: few years, a year, season, week, only a day
- The period of consideration can be divided on different time intervals Δt_i, where $T = \sum_{i=1}^{n} \Delta t_i$
- Hydro power systems from simple to complex technical hydraulically configuration and connectivity

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