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Simulation Models for Hydro-Electric Energy by Steady-Rate and Night-Shift-Pumped-Storage Operations

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ABSTRACT

New operation simulation models for hydroelectric energy and its financial benefit over an N-year period in daily time steps by the steady-rate and the open-loop night-shift-pumped-storage rules are developed. These models are applied on 11 existing dams in Türkiye, which reflect a wide range of hydrologic and hydraulic peculiarities, for regulations between 90% through 40% and the outputs are compared. Regulation is the ratio of (outflow for energy generation, hm^3/day) / (average inflow, hm^3/day). The present worth of energy benefits and of that of pumping costs computed with a discount rate of 9.5% over a 35-year period yield that the night-shift pumped-storage operations are more profitable than the steady-rate rule. Finally, generalized regression equations for average annual produced energy and for present worth of net benefits by both operation rules against statistically significant explanatory variables are developed using the results of these 11 dams, which are all meaningful by relevant statistical criteria.

Keywords: Reservoir operation, hydro-electric production by daily time steps, pumped-storage hydropower plants, renewable energy, water resources.

1. INTRODUCTION

According to a relevant report by the International Hydropower Association (IHA), the pumped-storage hydropower is the world's water battery because it provides flexible power services to grids since the beginning of the 20th century [1]. Zhang et al (2015) mention the advantages of the pumped-storage hydropower systems as balancing the peaking and dipping energy demands, providing reserve capacity, controlling frequency, and regulating phase fluctuations [2]. The pumped-storage hydropower is said to be the least-cost and hence the

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preferred means for storing energy for durations between 4 and 16 hours in the Highlights section of *U.S. Hydropower Market Report* [3].

In a fairly recent paper, having done detailed research by GIS and DEM analyses, considering the existing reservoirs having at most 20 km distance from each other, it is concluded that the realizable potential of pumped-storage hydropower of all of Europe including Türkiye is 28.7 TWh/year and of Türkiye alone is 19.63 TWh/year [4]. This means the pumped-storage hydropower potential of Türkiye accounts for 68% of the European total. In spite of this fact, unfortunately, there is not a single pumped storage system operating in Türkiye.

In the 'Proposed Measures to be Taken in The Near Future' Section of the *General Activities Report of the Year 2021* published by the General Directorate of State Hydraulic Works of Türkiye, recommendations are made about implementing pumped-storage hydropower systems by dams in cascade positions to serve for the same objectives as those expressed in the first paragraph above [5] (www.dsi.gov.tr).

The Official Gazette of Republic of Türkiye dated 12.2.2020 presents the list of projects of agreed upon and endorsed investments by then (https://www.resmigazete.gov.tr). One of these projects is a closed-loop system of pumped-storage to be formed by constructing an upper reservoir along with a hydropower plant (HPP) having a capacity of 1400 MW to be jointly operated with the present Gökçaya Dam and HPP. This project, which will be the first pumped-storage system in Türkiye, is to be carried out by the Joint Venture formed by two Japanese companies and one Turkish company. Aside from this tangible action for realization of a first pumped-storage hydropower system, there have been quite a few academic theses, technical reports, and papers about pumped-storage hydropower in Türkiye [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

Ak et al (2019) using 19-year long gauged monthly stream flows data, formed an objective function expressing the revenues gained by marketing the generated electricity minus the costs spent for pumping at night hours by the hydropower plants of three dams of Arkun, Yusufeli and Artvin, which are serially located in a cascading form on Coruh River [6]. Having solved the objective function using the package CONPOT, they determined that the net annual benefit of these three dams were greater when they were operated as if they had pumped storage hydropower plants than their present conventional hydropower operation. According to Ak et al (2019), in spite of suffering an energy loss about 15 ~ 25%, the pumped-storage systems provide technical benefits by regulating the fluctuations in electricity flow in the grid, and by taking advantage of the variations in electricity prices in parallel with demand patterns they also provide gains in financial revenues [6].

The main constraint of converting a dam into a pump storage facility is the excessive power needed to pump the same amount of water back up to the main reservoir. This fact includes two sub features. The first one is that the total head loss between the pump and the reservoir through the penstock must be added to the gross head. The second one is that the overall pump efficiency coefficient is in the denominator of the equation defining the power needed to run the pump. These two disadvantages analytically show up as: the power generated by the turbine is about 8*Q*(Hgross − Total head loss), whereas the power needed for the pump is about 12*Q*(Hgross + Total head loss) for the same gross head (Hgross) and the same discharge (Q) on the assumption that the overall turbine and pump efficiencies are tantamount at the value of 0.8155. Yet, the costs of either a reversible turbine-pump system or of a separate turbine-generator and motor-pump system are greater than that of a conventional turbine-generator unit.

Therefore, it is obvious that in order for a pumped-storage hydropower project to be feasible, the market unit price of the hydroelectric energy generated during the peak-demand period should be considerably higher than that of the low-demand time, the so-called energy arbitrage as pointed out by both Zhang et al [2] and Firis et al [13]. The price differences in parallel with the grid demands may also affect the overall financial benefit of even the conventional HPPs. A typical example for this case exists in the feasibility report of Karakurt Dam in Türkiye [17], in which the benefit/cost ratio of the overall project is computed by taking 0.10 $/kWh during the peak-demand period in a day and 0.06 $/kWh during rest of the day.

IHA classifies the pumped hydropower systems as 'closed-loop' and 'open-loop' [1] . The closed-loop systems consist of two reservoirs, not necessarily on a running stream, having a fairly high elevation difference from each other, and they circulate the same volume of water between the upper and the lower reservoirs, pumping when there is a low demand and ample extra energy in the grid, and generating during peak-demand periods. The cases mentioned by DSI (2022), Ak et al (2019), and Gimeno-Gutierrez and Lacal-Arantegui (2015) are about the open-loop systems [5, 6, 4] . There is a final disadvantage of the open-loop pumped-storage hydropower systems, which is the necessity for a sufficient volume capacity just downstream of the hydropower station to store water to be pumped back during the low-demand night period. If there is another dam downstream in cascade position and if the backwater extension of its reservoir stores a sufficient amount of water for pumping, this will be an ideal case. Otherwise, there should be a small dam downstream to store the extra volume of water to be pumped back. This problem can be solved at a minimal cost by placing the downstream cofferdam a little further downstream from the construction site before the beginning of the construction of the dam and its appurtenant structures.

The theme of this study is also about the open-loop systems. Here, the summary of comparing the outcomes of the operation rules of the steady-rate and of the night-shift-pumped-storage by applying them on 11 existing dams in Türkiye, which are selected within criteria based on low-high dam body height, small-large reservoir volume, low-high hydropower energy production capacity, is presented. The steady-rate rule aims to generate power at a constant pace on a 7/24 basis. The night-shift-pumped-storage rule splits a day's period in three segments called DAYTIME shift (11-hours-long between 06 and 17 hours), PEAK shift (5-hours-long between 17 and 22 hours), NIGHT shift (8-hours-long between 22 and 06 hours) as done by the Energy Market Regulatory Authority of Türkiye (known by the acronym EPDK in Türkiye) (www.epdk.gov.tr/Home/En). By the night-shift-pumped-storage rule energy is generated at full power capacity during the PEAK shift, and it is generated at a percentage between about 50% and 100% of full capacity during the DAYTIME shift. The extra volume of discharged water beyond the targeted release further downstream is pumped back up to the main reservoir during the NIGHT shift. We have developed models for operation simulations in daily time steps by these two rules and coded them as computer programs. Our models are of "sequential streamflow routing" type as called in *Engineering and Design HYDROPOWER* by USACE (1985) [18]. According to this relevant technical report, the sequential streamflow routing is the most detailed approach for determining the hydro-electric energy potential and the resultant financial benefits of hydropower dams, and yet analytically it is the most complex method [18]. A study of similar theme by the steady-rate rule was done by Sever and Yurtal using the package program HEC-ResSim on three dams sequentially positioned on Ceyhan River in Türkiye [19].

Each one of our models is concisely explained in the 'Method' section. As will be noticed having perused the 'Method' and the 'Results' sections, they have original details peculiar to themselves. For example, each package repeats the operations for 11 regulations of 90%, 85%, 70%, …, 45%, 40%, all executed in a single run. Regulation is the ratio of (outflow for energy generation, hm^3/day)/(average inflow, hm^3/day). The objectives of this study are (1) to summarize the formulations and the steps of these newly developed models, (2) to apply the coded programs executing these models to 11 dams serving for hydropower generation in Türkiye, and (3) to determine generalized relationships for the average annual energy and the net financial benefit relating them to effective explanatory variables by these two different operation rules.

2. CASE STUDIES

Table 1 gives the names of 11 existing dams having hydropower plants in Türkiye along with characteristic information about them.

Table 1 - Descriptive data of dams used in this study

Name of dam	Name of stream	Active storage capacity (hm^3)	Average annual inflow (hm^3/yr)	Maximum gross head (m)	Type and number of turbines	Turbine design head (m)	Turbine design discharge (m^3/s)
Ağaçhisar	Orhaneli	77.8	526	75	Francis (2)	70	16.5
Altınkaya	Kızılırmak	2893	5755	133	Francis (4)	126	172
Bahçelik	Zamantı	185	333	29	Kaplan (3)	25	11.3
Berdan	Berdan	156	1632	39	Francis (2)	33	50
Ermenek	Ermenek	1747	1459	360	Francis (2)	327	53
Hasan Uğurlu	Yeşilırmak	662	5417	126	Francis (4)	121	128
Karakurt	Aras	447	1329	134	Francis (3)	130	2×46, 1×10
Kılıçkaya	Kelkit	831	2212	98	Francis (2)	91	83
Susurluk	Simav	165	1095	32	Kaplan (2)	30	60
Yamula	Kızılırmak	2020	2123	105	Francis (2)	97	55
Yedigöze	Seyhan	300	4425	95	Francis (2)	91	190

The stream-gauging stations 1501-Yamula, 1533-İnözü, 1818-Üçtepe, 1823-Emegil are almost at the same cross-sections where Yamula, Altınkaya, Yedigöze, and Bahçelik dams are located. The construction of Yamula dam was completed in 2004. The gauging record of

1501-Yamula began in 1939, and there are no missing records since then. The unregulated 35-year-long daily flows series between the years 1969 and 2003 are taken as the inflows to Yamula dam. The construction of Yedigöze dam was completed in 2011. The gauging at this station began in 1966 and continued until 2010 incessantly. The 35-year-long daily flows between the years 1976 and 2010 measured at station 1818-Üçtepe are considered to be the inflows to Yedigöze dam. The construction of Bahçelik dam was completed in the year 2012; but the station was closed in 2000. The gauging at 1823-Emegil began in 1974. In order to complete the record length to 35 years, the missing 8-year-long part between 2001 and 2008 was approximately computed by the drainage-area-ratio formula using the daily flows gauged at the close-by gauging station 1834-Kılıçmehmet.

There are not any gauging stations close enough to the embankments of the other seven dams. By investigating the beginning and ending record lengths of the nearest-by gauging stations around those seven dams and by choosing the most suitable stations, the 35-year-long gauged daily flows are approximately computed for them again by the drainage-area-ratio formula, by the procedure proposed in a relevant study [20].

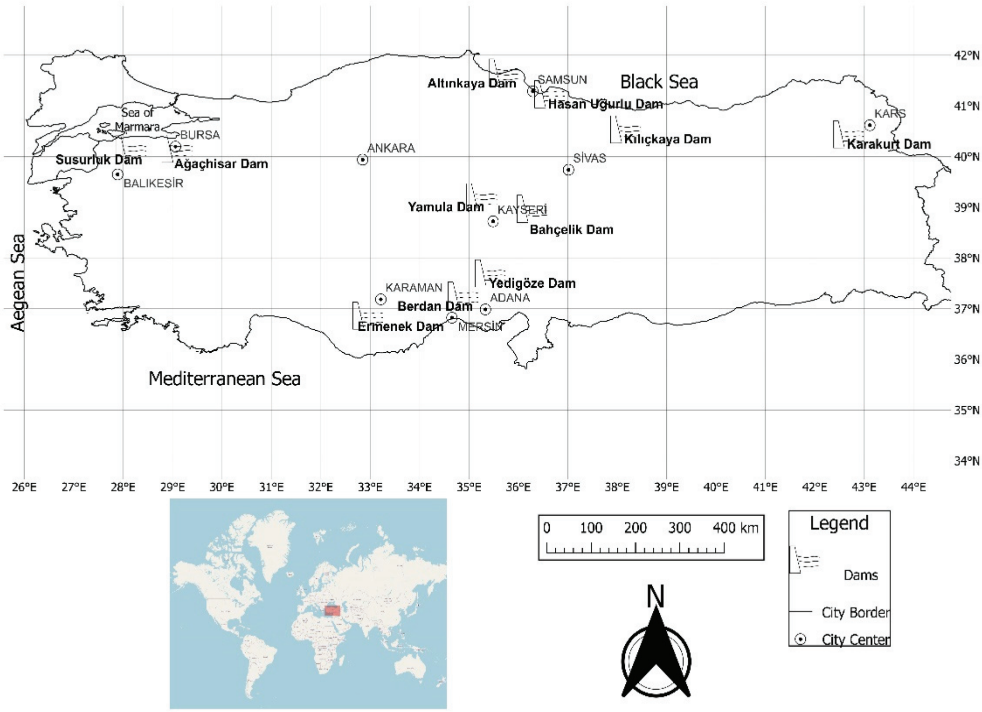

Figure 1 - Map of case study dams

All of the necessary technical data of the pipes constituting the penstocks such as the lengths, diameters, materials, and other peculiarities like bends, contractions, and valves were taken from the final project drawings of these 11 dams. Similarly, the storage volume (hm^3) and the lake surface area (km^2) against the lake water surface elevation (m) relationships were also obtained from their final project drawings. The pan evaporation data in mm/day units at meteorological stations close-by to the reservoirs were obtained from the Turkish State Meteorological Service. A map of the case study dams created using the Free and Open Source QGIS software is given in Figure 1 [21, 22].

3. METHOD

3.1. Common Parts of the Two Simulation Models

The reservoir is top full at the beginning of an operation period of N years; namely, S_0 = Smax and WSE_0 = WSEmax, where S_0 is the volume of water in the reservoir and WSE_0 is the lake water surface elevation at the beginning of the first day of operations, WSEmax is the maximum operation elevation which is the top of active pool, and Smax is the volume of reservoir under WSEmax. The operation in a day is simulated by

$$S_{i,j,k} = S_{i-1,j,k} + I_{i,j,k} - EL_{i,j,k} - \sum_{s=1}^{NS} Os_{i,j,k} \qquad (1)$$

Here, $S_{i-1,j,k}$ and $S_{i,j,k}$ are the volumes of water in the reservoir at the beginning and at the end of the i'th day of the j'th month of the k'th year (hm^3), $I_{i,j,k}$ is the inflow (hm^3/day), $EL_{i,j,k}$ is the loss of evaporation from the lake surface (hm^3/day), $Os_{i,j,k}$ is the flow released through the s'th spillway (hm^3/day) during the i'th day, and NS is the number of spillways. i varies from 1 through 30 for November, April, June, September, 1 through 31 for October, December, January, March, May, July, August, 1 through 28 for February and 1 through 29 for February every other four years. j varies from 1 through 12 and k varies from 1 through N. j=1 is October and j=12 is September. There are at least two spillways in a dam having a hydropower plant (HPP): the penstock and the flood spillway. There may be more spillways for other releases like irrigation and municipal waters.

We compute the evaporation loss by multiplying the lake surface area in km^2 at the beginning of the i'th day by 80% of daily pan evaporation value in m/day measured at a nearby meteorological station.

The water surface elevations of the tail-water pond in m is given against the total released discharges in m^3/s in form of two numerical columns at small enough increments of discharge in the input data file. The gross head of the penstock at the end of the i'th day is computed by

$$Hgr_{i,j,k} = WSE_{i,j,k} - TWS_{i,j,k} \qquad (2)$$

The average gross head during the i'th day is computed as the average of the gross heads at the beginning and at the end of the i'th day by

$$\overline{Hgr}_{i,j,k} = (Hgr_{i-1,j,k} + Hgr_{i,j,k})/2 \qquad (3)$$

In some dams, there is one shaft spillway which branches in the powerhouse into as many pipes as the number of turbines by means of a manifold (e.g. Yamula dam). In some other dams, there are as many pipes as the number of turbines in parallel layouts from the intake down to the powerhouse (e.g. Yedigöze dam). Our models simulate both cases properly. We denote the number of pressure conduits culminating in the powerhouse by NP. The total head loss in m throughout the p'th pipe during the i'th day is computed by

$$\mathrm{THLp}_{i,j,k} = \mathrm{Cp} * \mathrm{Qp}_{i,j,k}^{2} \quad (4)$$

Here, Cp is the overall loss coefficient for the p'th pipe accounting for all the friction and local losses from the trash rack down to the exit of the draft tube, $Qp_{i,j,k}$ is the discharge in m^3/s through the p'th pipe during the i'th day. With the help of another computer program, the numerical value of the Cp coefficient is obtained beforehand taking into account all geometrical and hydraulic peculiarities pertaining to that pipe covering a wide range of discharges up to the maximum capacity [23].

The average net head on the turbine at the end of the p'th pipe during the i'th day is computed by

$$\overline{\mathrm{Hnetp}}_{i,j,k} = \overline{\mathrm{Hgr}}_{i,j,k} - \mathrm{THLp}_{i,j,k} \quad (5)$$

3.2. Steady-Rate Operation Simulation

The relation between the target discharge to be released through the energy spillway in hm^3/day ($Qes_{i,j,k}$) and the same discharge in m^3/s ($Qest_{i,j,k}$) is

$$\mathrm{Qest}_{i,j,k}\ (\mathrm{m}^3/\mathrm{s}) = \mathrm{Qes}_{i,j,k}\ (\mathrm{hm}^3/\mathrm{day}) * (10^6/86400) \quad (6)$$

The maximum capacity discharge in m^3/s of a single turbine unit, denoted by Qt_{max}, is determined beforehand by the designers considering all the relevant geometric and hydraulic peculiarities pertaining to the head race, tail race conditions and the chosen turbine properties. If NP = 1, then $Qest_{i,j,k} \leq Qt_{max}$. If NP > 1, then as many pipes as the integer part of the division of ($Qest_{i,j,k}$ / Qt_{max}), denoted by NFP, will flow with full capacity while one pipe will convey as much a discharge as ($Qest_{i,j,k}$ – NFP*Qt_{max}). Let NT denote the number of turbines. And, the net power generated by a turbine-generator-transformer unit is determined by

$$\mathrm{Pp}_{i,j,k} = \eta * \gamma * \mathrm{Qtp}_{i,j,k} * \overline{\mathrm{Hnetp}}_{i,j,k} \quad (7)$$

Here, η is the overall efficiency which equals multiplication of individual efficiencies of the turbine, the generator, and the transformer, γ is the unit weight of water in kN/m^3, $Pp_{i,j,k}$ is the net power to generate electric energy by that turbine in kW. In Section 7 of *Standard Handbook of Power Plant Engineering* it is suggested that 0.815 is a reasonable value for η [24]. In *Engineering and Design HYDROPOWER* by USACE (1985), it is written: "A value of 80 to 85 percent can be used prior to turbine selection, but once a turbine design has been chosen, an average efficiency based on the characteristics of that unit should be used." [18]. In a technical report about the hydropower potential of Sır Dam in Türkiye, 0.866 is taken for η [25] The efficiency of the transformer is the highest and about 0.98. Next comes the efficiency of the generator, which according to USACE (1985), is between 0.95 and 0.98

[18]. The turbine efficiency depends on the specific velocity and hence on both the discharge through and the net head on the turbine and also on the type and brand name of the turbine. When both are operated at their optimum heads and discharges, the efficiency of the Pelton turbines is said to be a little higher than that of the Francis turbines (e.g. [26]). Generally, the efficiency of Francis turbines varies between 0.70 and 0.92, and for close to optimum ranges, their efficiency is in the range: 0.80 and 0.92 [18, 26]. Our models use an average value for $\eta^*\gamma$ in the range: 8.0 − 8.5 given by the user.

There are operable ranges of net head and turbine discharge depending on type of the turbine (e.g. [18, 24, 26]). The efficiency at heads and discharges higher than the design values will be close to the design conditions. The lower bounds are problematic. Much lower discharges and heads than the design values may cause cavitation damage on the runner blades, vibration of the unit and will result in too low an efficiency. Table 5-1 in *Engineering and Design HYDROPOWER* by USACE (1985) and Table 4.2 in *Hydropower Engineering Handbook* (Gulliver and Arndt 1991) offer operable ranges of heads, discharges, and powers for various types of turbines [18, 26]. In our models, we specify a lower bound for the power accounting for the effects of head and discharge jointly, and we suggest this to be 25% of the rating capacity. In any day, the turbine is shut off when the net power by that turbine turns out to be smaller than this lower-bound value and power is not generated. That discharge is not released downstream and the unreleased amount is recorded as the shortage of that day from the target release.

The total power generated by the HPP of the dam in the i'th day is computed by

$$\mathrm{Ptotal}_{i,j,k} = \sum_{p=1}^{NT} \mathrm{Pp}_{i,j,k} \tag{8}$$

Here, $\mathrm{Pp}_{i,j,k}$ is the net power by the p'th turbine in the i'th day in kW. If the energy shaft spillway is of a single pipe, then the total power is computed by equation (7), which is distributed to NT number of turbines in the powerhouse in proportion to their capacities.

The energy produced in a normal day is computed by

$$\mathrm{HEE}_{i,j,k} = \mathrm{Ptotal}_{i,j,k} * 24 \tag{9}$$

Here, $\mathrm{HEE}_{i,j,k}$ is the energy generated in the i'th day in kWh/day. Next, the monthly energy produced is computed by

$$\mathrm{MHEE}_{j,k} = \sum_{i=1}^{\text{iend-j}} \mathrm{HEE}_{i,j,k} \tag{10}$$

Here, iend-j equals one of 30, 31, 28, 29 depending on the j'th month, $\mathrm{MHEE}_{j,k}$ is the generated energy in the j'th month of the k'th year in kWh/month. Next, the annual energy produced in the k'th year in kWh/year is computed by

$$\mathrm{AHEE}_{k} = \sum_{j=1}^{12} \mathrm{MHEE}_{j,k} \tag{11}$$

The minimum of 365.25*N $\mathrm{HEE}_{i,j,k}$'s is known as the 'firm energy' (FE) [18]. In any day, the difference of the energy of that day from the firm energy is called the 'secondary energy'.

Because the firm energy is available in any day over the entire N year period, it is treated as an assured energy and that is why its unit price is a little greater than the secondary energy. The annual financial benefit due to marketing of the produced energy in the k'th year is computed by

$$\mathrm{FB_k} = 365 * \mathrm{FE} * \text{UP-FE} + \sum_{j=1}^{12} \sum_{i=1}^{\text{iend-j}} (\mathrm{HEE_{i,j,k}} - \mathrm{FE}) * \text{UP-SE} \tag{12}$$

Until 2015, in Türkiye the unit prices of the firm and the secondary energies were taken as: UP-FE = 0.06 $/kWh and UP-SE = 0.033 $/kWh. By a circular issued in 2015 by the General Directorate of State Hydraulic Works [27], the concepts of firm and secondary energies are abolished and a steady unit price for hydroelectric energy is adopted. Our model by the steady-rate rule still determines the firm energy and computes the financial accounts of the firm and the secondary energies separately. However, in the current study we have given the same numerical value for both, which is 0.04 $/kWh.

The overall financial benefit is computed by

$$\mathrm{PWFB} = \sum_{k=1}^{N} \mathrm{FB_k} * (1 + \mathrm{dr})^{-k} \tag{13}$$

Here, dr is the discount ratio, which is being taken as 0.095 over the last few decades in Türkiye (e.g. [27]) and PWFB is the present worth of the financial benefits by the produced energy at the beginning of the N-year operation period in Dollars.

Our models generate extra energy by releasing greater discharges than the target discharge through the energy spillway during a day in which the lake water surface elevation is equal to or very close to the maximum operation elevation (top of active pool) when a high inflow comes such that the lake water surface elevation at the end of the day will exceed the top of active pool. During such a day all of the turbines will run at or close to their maximum capacity discharges and extra energy is produced by surplus waters which would otherwise be discarded over the flood spillway. For a mild flood the excessive waters may be small enough to be taken up by the turbines. As an example, while the average inflow to Altınkaya Dam is 182 m^3/s, the total discharge of its four turbines when all run at full capacity is 688 m^3/s, about 3.8 times the average inflow. For a massive flood however, the excessive amount of flows left over from fully operating turbines will still be conveyed over the flood spillway. The surplus amount of water in such a day is given by

$$\mathrm{Surplus_{i,j,k}} = \mathrm{S_{i-1,j,k}} + \mathrm{I_{i,j,k}} - \mathrm{EL_{i,j,k}} - \sum_{s=1}^{NS-2} \mathrm{Os_{i,j,k}} - \mathrm{S_{max}} \tag{14}$$

Here, NS−2 is the number of spillways other than the flood spillway and the energy spillway (penstock) and $Surplus_{i,j,k}$ is the surplus amount of water in the i'th day in hm^3/day that can be diverted through the penstock. If $Surplus_{i,j,k}$ is greater than the sum of capacity discharges of NP pipes of the energy spillway, then all of the turbines will run with their maximum discharges, and as much water as ($Surplus_{i,j,k} - NP*Qt_{max}*86400/10^6$) in hm^3/day will flow over the flood spillway. If $Surplus_{i,j,k} < NP*Qt_{max}*86400/10^6$, then that means a mild flood is effective while the lake is top full whose excess waters will all be taken up by the energy spillway. In such a day, the integer part of the division: [($Surplus_{i,j,k}*10^6/86400$) / Qt_{max}] gives the number of turbines running at full capacity, denoted by NTF and one turbine will run with a discharge: [($Surplus_{i,j,k}$*10^6/86400) − NTF*Qt_{max}]. The total head losses, the generated powers and energies are computed by the equations given above.

Throughout the simulation, those discharges for purposes other than the energy generation depending on their priorities in a day are either reduced or completely shut off when the lake water surface elevation equals the minimum operation elevation (bottom of active pool) or very close to that when little amount of inflow comes such that the lake water surface elevation at the end of the day will become less than or equal to the bottom of active pool. In that day a shortage from the targeted energy discharge also may occur and hence small power and small energy is generated. In such a day, the power that could be generated may fall below the lower-limit value peculiar to the used turbine, and hence, no flow is discharged through any turbine, zero power is generated, and the target energy spillway flow of that day in hm^3/day is recorded as a shortage in release further downstream of the dam. In such a critical day, the amount of water left for possible but little amount of power is given by

$$\mathrm{Left}_{i,j,k} = \mathrm{S}_{i-1,j,k} + \mathrm{I}_{i,j,k} - \mathrm{EL}_{i,j,k} - \sum_{s=1}^{NS-2} \mathrm{Os}_{i,j,k} - \mathrm{S}_{min} \tag{15}$$

The discharge that can be released through a turbine in m^3/s equals ($Left_{i,j,k}$*10^6/86400).

3.3. Night-Shift-Pumped-Storage Operation Simulation

All of the turbines run at their maximum capacities during the PEAK shift. The turbines run with a discharge in proportion to their maximum capacities during the DAYTIME shift. The ratio of DAYTIME discharge to the maximum penstock discharge, which is within the range: 0.5 - 1.0, is initially assigned by the user. The difference of the volume of water released during the DAYTIME and PEAK shifts from the target release further downstream is pumped back up to the main reservoir during the NIGHT shift. The durations of these within-day shifts are determined by the Energy Market Regulatory Authority (EPDK). The user of the program can give durations different from the ones adopted by EPDK.

3.3.1. Energy Produced During the PEAK Shift and its Financial Worth

If the energy spillway is a single pipe branching into as many small pipes as the number of turbines, then the total head loss, the average net head on each one of the turbines, and the generated power during the PEAK shift of the i'th day are computed as follows.

$$\mathrm{THL}_{\mathrm{peak}_{i,j,k}} = \mathrm{C} * (\mathrm{NT} * \mathrm{Qt}_{max})^2 \tag{16}$$

$$\overline{\mathrm{Hnet}}_{\mathrm{peak}_{i,j,k}} = \overline{\mathrm{Hgr}}_{i,j,k} - \mathrm{THL}_{\mathrm{peak}_{i,j,k}} \tag{17}$$

$$\mathrm{Ppeaktotal}_{i,j,k} = \eta * \gamma * \mathrm{NT} * \mathrm{Qt}_{max} * \overline{\mathrm{Hnet}}\mathrm{peak}_{i,j,k} \tag{18}$$

In these equations, C is the total head loss coefficient of the energy spillway including the branching-pipe local loss and the exit velocity head of the draft tube of a turbine.

If the energy spillway consists of as many pipes as the number of turbines from the intake at the forebay down to the tailrace, then the total head loss, the average net head, and the generated power during the PEAK shift of the i'th day are computed as follows.

$$\mathrm{THL_{peak}p_{i,j,k}} = \mathrm{Cp} * \mathrm{Qt_{max}}^2 \tag{19}$$

$$\overline{\mathrm{Hnet}}_{\mathrm{peak}}\mathrm{p_{i,j,k}} = \mathrm{Hgr_{i,j,k}} - \mathrm{THL_{peak}p_{i,j,k}} \tag{20}$$

$$\mathrm{P_{peak}p_{i,j,k}} = \eta * \gamma * \mathrm{Qtmax} * \overline{\mathrm{Hnet}}_{\mathrm{peak}}\mathrm{p_{i,j,k}} \tag{21}$$

$$\mathrm{P_{peak}total_{i,j,k}} = \sum_{p=1}^{NT} \mathrm{P_{peak}p_{i,j,k}} \tag{22}$$

Here, Cp is the total head loss coefficient of the p'th pipe.

In either case, the produced energy and its financial benefit during the PEAK shift of the i'th day are computed by

$$\mathrm{HEE_{peak_{i,j,k}}} = \mathrm{P_{peak}total_{i,j,k}} * \mathrm{D_{peak}} \tag{23}$$

$$\mathrm{FB_{peak_{i,j,k}}} = \mathrm{HEE_{peak_{i,j,k}}} * \mathrm{UP_{peak}} \tag{24}$$

Here, D_{peak} is the duration of the PEAK shift in hours, UP_{peak} is the unit marketing price of energy produced during the PEAK shift.

The volume of water released through the energy spillway in hm^3/day during the PEAK shift of the i'th day while all of the turbines are running with their maximum capacity discharges, $Qes_{peaki,j,k}$, is

$$\mathrm{Qes_{peak_{i,j,k}}} = \mathrm{NT} * \mathrm{Qt_{max}} * \mathrm{D_{peak}} * 3600/10^6 \tag{25}$$

3.3.2. Energy Produced During the DAYTIME Shift and its Financial Worth

The upper limit for volume of water that can be released through the energy spillway during the DAYTIME shift is equal to the sum of the maximum capacity discharges of all of the turbines running throughout the DAYTIME shift. And, the lower limit equals the daily target release minus the volume of water discharged during the PEAK shift. The below inequalities depict these verbally expressed bounds.

$$(\mathrm{Qes_{i,j,k}} - \mathrm{Qes_{peak_{i,j,k}}}) < \mathrm{Qesdaytime_{i,j,k}} < (\mathrm{NT} * \mathrm{Qt_{max}} * \mathrm{Ddaytime} * 3600/10^6) \tag{26}$$

Here, $Qes_{i,j,k}$ is the daily target release for energy production in hm^3/day, also called target penstock release, $Qesdaytime_{i,j,k}$ is the volume of water released through the energy spillway in hm^3/day during the DAYTIME shift of the i'th day, Ddaytime is the duration of the DAYTIME shift in hours, and obviously this expression is valid for a daily target energy spillway release greater than the amount discharged during the PEAK shift. In that case, if

$Qesdaytime_{i,j,k}$ equals the lower bound of this inequality, then there is no amount of water to be pumped back up to the main reservoir.

Labeling a ratio as: "ratio of daytime penstock target release" (symbolized by RDPR) which equals (actual DAYTIME penstock discharge in m^3/s)/(maximum possible penstock discharge in m^3/s), taking Ddaytime as 11 hours and Dpeak as 5 hours, the algebraic manipulations lead to the following boundaries for RDPR.

$$\{Qes_{i,j,k} \div [0.0396 * NT * Qt_{max}]\} - 0.4545455 < RDPR < 1.0 \tag{27}$$

Here, Qt_{max} is the maximum capacity discharge of one of NP number of pipes constituting the penstock. Having chosen a magnitude for RPDR within these bounds, the discharge of energy spillway during the DAYTIME shift in m^3/s units is computed by

$$Qesdaytimet_{i,j,k} = RDPR * NT * Qt_{max} \tag{28}$$

The number of turbines running at their maximum capacities during the DAYTIME shift equals the integer part of the division ($Qesdaytime\text{-}t_{i,j,k}$ / Qt_{max}). Denoting this number by NTD, one turbine other than NTD turbines runs with a discharge: $Qesdaytimet_{i,j,k} - NTD*Qt_{max}$.

If the energy spillway is a single pipe branching into as many small pipes as the number of turbines, then the total head loss, the average net head on each one of the turbines, and the generated power during the DAYTIME shift of the i'th day are computed as follows.

$$THL\text{-}daytime_{i,j,k} = C * {Qesdaytimet_{i,j,k}}^2 \tag{29}$$

$$\overline{Hnet}daytime_{i,j,k} = \overline{Hgr}_{i,j,k} - THLdaytime_{i,j,k} \tag{30}$$

$$Pdaytimetotal_{i,j,k} = \eta * \gamma * Qesdaytimet_{i,j,k} * \overline{Hnet}daytime_{i,j,k} \tag{31}$$

If the energy spillway consists of as many pipes as the number of turbines, then the total head loss and the average net head in NTD number of pipes, and the generated power at NTD turbines during the DAYTIME shift are the same as those of the PEAK shift. The total head loss and the average net head in the pipe carrying a smaller-than-maximum discharge and the power generated by the turbine at the end of that pipe are computed by equations (19), (20), (21) by substituting ($Qesdaytimet_{i,j,k} - NTD*Qt_{max}$) for Qt_{max}. Next, the generated power during the DAYTIME shift of the i'th day is computed by

$$Pdaytimetotal_{i,j,k} = \sum_{p=1}^{NDT+1} Pdaytimep_{i,j,k} \tag{32}$$

In either case, the produced energy and its financial benefit during the DAYTIME shift of the i'th day are computed by

$$HEEdaytime_{i,j,k} = Pdaytimetotal_{i,j,k} * Ddaytime \tag{33}$$

$$\mathrm{FBdaytime}_{i,j,k} = \mathrm{HEEdaytime}_{i,j,k} * \mathrm{UPdaytime} \quad (34)$$

Here, UPdaytime is the unit marketing price of energy produced during the DAYTIME shift.

3.3.3. Energy Produced During the NIGHT Shift and its Financial Worth

At the beginning of an i'th day, if the reservoir water surface elevation is equal to or very close to the top of active pool and the inflow in that day is too much so as to cause the lake water level at the end of the day to exceed the top of active pool, then, all of the turbines are run at their full capacities during the DAYTIME shift also. Namely, regardless of the target energy release, the actual DAYTIME release is increased to the value of the upper bound of inequality (26). If the maximum operation elevation is still exceeded with all of the turbines operating at full capacities during both the DAYTIME and the PEAK shifts, then pumping during the NIGHT shift is not done since there is not available storage volume in the reservoir. Instead, energy is generated during the NIGHT shift as well using some of these surplus waters which would otherwise be discharged by the flood spillway. The volume of water in hm^3/day which will be used for power generation during the NIGHT shift of such a day equals the smaller one of those computed by the two equations below.

$$\mathrm{Qesnight}_{i,j,k} = \mathrm{Surplus}_{i,j,k} - [(\mathrm{NT} * \mathrm{Qt}_{\mathrm{max}} * \mathrm{Ddaytime}_{\mathrm{peak}} * 3600)/10^6] \quad (35a)$$

$$\mathrm{Qesnight}_{i,j,k} = (\mathrm{NT} * \mathrm{Qt}_{\mathrm{max}} * \mathrm{Dnight} * 3600)/10^6 \quad (35b)$$

Here, $\mathrm{Ddaytime}_{peak}$ equals the sum of Ddaytime plus D_{peak}, Dnight is the duration of the HIGHT shift in hours, and $\mathrm{Surplus}_{i,j,k}$ is the surplus amount of water given by equation (14). Conversion of $\mathrm{Qesnight}_{i,j,k}$ from hm^3/day to m^3/s units is done by

$$\mathrm{Qesnightt}_{i,j,k} = (\mathrm{Qesnight}_{i,j,k} * 10^6)/(\mathrm{Dnight} * 3600) \quad (36)$$

The number of turbines running with their maximum capacity discharges equals the integer part of the division of ($\mathrm{Qesnightt}_{i,j,k}$ / Qt_{max}), which could be zero if $\mathrm{Qesnightt}_{i,j,k} < \mathrm{Qt}_{max}$. Denoting this number by NTN, one turbine other than NTN turbines runs with a discharge: $\mathrm{Qesnightt}_{i,j,k} - \mathrm{NTN}*\mathrm{Qt}_{max}$.

If the energy spillway is a single pipe branching into as many small pipes as the number of turbines, then the total head loss, the average net head on each one of the turbines, and the generated power during the NIGHT shift of the i'th day are computed as follows.

$$\mathrm{THLnight}_{i,j,k} = \mathrm{C} * {\mathrm{Qesnightt}_{i,j,k}}^2 \quad (37)$$

$$\overline{\mathrm{Hnet}}\mathrm{night}_{i,j,k} = \overline{\mathrm{Hgr}}_{i,j,k} - \mathrm{THLnight}_{i,j,k} \quad (38)$$

$$\mathrm{Pnighttotal}_{i,j,k} = \eta * \gamma * \mathrm{Qesnightt}_{i,j,k} * \overline{\mathrm{Hnet}}\mathrm{night}_{i,j,k} \quad (39)$$

If the energy spillway consists of as many pipes as the number of turbines, then the total head loss and the average net head in NTN number of pipes, and the generated power at NTN turbines during the NIGHT shift are the same as those of the PEAK shift. The total head loss and the average net head in the pipe carrying a smaller-than-maximum discharge and the power generated by the turbine at the end of that pipe are computed by equations (19), (20), (21) by substituting ($Qesnightt_{i,j,k} - NTN*Qt_{max}$) for Qt_{max}. Next, the generated power during the NIGHT shift of the i'th day is computed by

$$\text{Pnighttotal}_{\text{i,j,k}} = \sum_{\text{p=1}}^{\text{NTN+1}} \text{Pnight-p}_{\text{i,j,k}} \tag{40}$$

In either case, the produced energy and its financial benefit during the NIGHT shift of the i'th day are computed by

$$\text{HEEnight}_{\text{i,j,k}} = \text{Pnighttotal}_{\text{i,j,k}} * \text{Dnight} \tag{41}$$

$$\text{FBnight}_{\text{i,j,k}} = \text{HEEnight}_{\text{i,j,k}} * \text{UPnight} \tag{42}$$

Here, UPnight is the unit marketing price of energy produced during the NIGHT shift.

3.3.4. Energy Consumed for Pumping During the NIGHT Shift and its Financial Cost

At the end of a normal day of operations, the volume of water in the reservoir will be between the dead storage and (dead storage + active storage capacity) ($Smin < S_{i,j,k} < Smax$). In such a day, all turbines run at their full capacities during the PEAK shift and the total volume of energy flows during the DAYTIME shift, $Qesdaytime_{i,j,k}$, will be between the lower and upper bounds of inequality (26), which is decided on by the operators of the dam. Then, the flowrate of water in m^3/s to be pumped back up to the main reservoir during the NIGHT shift, $Qpumpt_{i,j,k}$, is computed by

$$\text{Qpumpt}_{\text{i,j,k}} = \left(\text{Qes}_{\text{peak}_{\text{i,j,k}}} + \text{Qesdaytime}_{\text{i,j,k}} - \text{Qes}_{\text{i,j,k}}\right) * 10^6/(3600 * \text{Dnight}) \tag{43}$$

In this study, we assume that the turbo-machinery units are either reversible turbine-pump types or ternary systems having a common shaft.

We use the term Qpumpmax denoting the maximum capacity discharge of a pump, which will be a close value to that of a turbine, Qt_{max}. Both Qt_{max} and $Qpump_{max}$ are predetermined values computed by the project designers of the dam and the hydropower plant. Then, the number of pumps running at their maximum capacities during the NIGHT shift equals the integer part of the division ($Qpumpt_{i,j,k}$ / $Qpump_{max}$). Denoting this number by NPN, one pump other than NPN pumps runs with a discharge: $Qpumpt_{i,j,k} - NPN*Qpump_{max}$.

If the energy spillway is a single pipe branching into as many small pipes as the number of turbines, then the total head loss, the average net head on each one of the pumps, and the power consumed by all of the pumps during the NIGHT shift of the i'th day are computed as follows.

$$\text{THLpump}_{\text{i,j,k}} = \text{Cpump} * {\text{Qpumpt}_{\text{i,j,k}}}^2 \tag{44}$$

$$\overline{\text{Hnet}}\text{pump}_{\text{i,j,k}} = \overline{\text{Hgr}}_{\text{i,j,k}} + \text{THLpump}_{\text{i,j,k}} \tag{45}$$

$$\text{Ppumptotal}_{\text{i,j,k}} = \gamma * \text{Qpumpt}_{\text{i,j,k}} * \overline{\text{Hnet}}\text{pump}_{\text{i,j,k}} \, / \, \eta\text{pump} \tag{46}$$

In these equations, Cpump is the total head loss coefficient of the pipe used for pumping when the flow is in reverse direction, ηpump is the overall pumping efficiency. Equations (44) and (45) are valid for any system, whether it is the same pipe of a reversible turbine-pump unit or of a ternary unit or even if the pumping is done through a separate pipe.

If the energy spillway consists of as many pipes as the number of turbines, then the total head loss and the average net head in each one of NPN number of pipes, and the power needed for each pump during the NIGHT shift are computed as follows.

$$\text{THLpumpp}_{\text{i,j,k}} = \text{Cpumpp} * \text{Qpump}_{max}{}^{2} \tag{47}$$

$$\overline{\text{Hnet}}\text{pumpp}_{\text{i,j,k}} = \overline{\text{Hgr}}_{\text{i,j,k}} + \text{THLpumpp}_{\text{i,j,k}} \tag{48}$$

$$\text{Ppumpp}_{\text{i,j,k}} = \gamma * \text{Qpumpmax} * \overline{\text{Hnet}}\text{pumpp}_{\text{i,j,k}} \, / \, \eta\text{pumpp} \tag{49}$$

The total head loss and the average net head in the pipe in which a smaller-than-maximum discharge is pumped, and the power needed for that pump during the NIGHT shift are computed by equations (47) − (49) by inserting ($\text{Qpumpt}_{\text{i,j,k}}$ − NPN*$\text{Qpump}_{\text{max}}$) for $\text{Qpump}_{\text{max}}$. The total power needed for all of the running pumps are computed by

$$\text{Ppumptotal}_{\text{i,j,k}} = \sum_{\text{p=1}}^{\text{NPN+1}} \text{Ppumpp}_{\text{i,j,k}} \tag{50}$$

In either case, the energy needed for pumping during the NIGHT shift of the i'th day and its financial cost are computed by

$$\text{EEpump}_{\text{i,j,k}} = \text{Ppumptotal}_{\text{i,j,k}} * \text{Dnight} \tag{51}$$

$$\text{FCpump}_{\text{i,j,k}} = \text{HEEpump}_{\text{i,j,k}} * \text{UCpump} \tag{52}$$

Here, UCpump is the unit cost of energy consumed for pumping during the NIGHT shift.

3.3.5. Daily, Monthly, and Yearly Produced Energies and Their Financial Benefits

The generated energy and its financial benefit in an i'th day are computed as follows.

$$\text{HEE}_{\text{i,j,k}} = \text{HEEdaytime}_{\text{i,j,k}} + \text{HEE}_{\text{peak}_{\text{i,j,k}}} + \text{HEEnight}_{\text{i,j,k}} \tag{53}$$

$$\text{FB}_{\text{i,j,k}} = \text{FBdaytime}_{\text{i,j,k}} + \text{FB}_{\text{peak}_{\text{i,j,k}}} + \text{FBnight}_{\text{i,j,k}} \tag{54}$$

The monthly and yearly generated energies are computed by equations (10) and (11), and their financial benefits are computed as follows.

$$\text{MFB}_{\text{j,k}} = \sum_{\text{i=1}}^{\text{iend-j}} \text{FB}_{\text{i,j,k}} \tag{55}$$

$$\mathrm{YFB_k} = \sum_{j=1}^{12} \mathrm{MFB_{j,k}} \tag{56}$$

The monthly and yearly energies spent for pumping and their financial costs are computed as follows.

$$\mathrm{EEpump_{j,k}} = \sum_{i=1}^{\mathrm{iend\text{-}j}} \mathrm{EEpump_{i,j,k}} \tag{57}$$

$$\mathrm{FCpump_{j,k}} = \sum_{i=1}^{\mathrm{iend\text{-}j}} \mathrm{FCpump_{i,j,k}} \tag{58}$$

$$\mathrm{YEEpump_k} = \sum_{j=1}^{12} \mathrm{EEpump_{j,k}} \tag{59}$$

$$\mathrm{YFCpump_k} = \sum_{j=1}^{12} \mathrm{FCpump_{j,k}} \tag{60}$$

The net difference of yearly financial benefit on account of marketing the generated energies from the yearly cost accrued due to the electrical energy charged to the pump motors is computed by

$$\mathrm{NFB_k} = \mathrm{YFB_k} - \mathrm{YFCpump_k} \tag{61}$$

3.4. Present worth Values at the Beginning of an N-Year Operation Period and Overall Optimization

The present worth at the beginning of an N-year operation period of either the benefits by marketing the produced energy or the costs of energy consumed by pumping taking into account the time value of money in proportion to the adopted discount ratio (dr) is computed by the known formula as follows.

$$\mathrm{PWFB} = \sum_{k=1}^{N} \mathrm{YFB_k} * (1 + \mathrm{dr})^{-k} \tag{62}$$

$$\mathrm{PWFCpump} = \sum_{k=1}^{N} \mathrm{YFCpump_k} * (1 + \mathrm{dr})^{-k} \tag{63}$$

And, the present worth of the net income by the night-shift-pumped-storage rule is computed by

$$\mathrm{PWFBnet} = \mathrm{PWFB} - \mathrm{PWFCpump} \tag{64}$$

The operation simulation models in daily time steps by a definite regulation summarized heretofore determine that average energy spillway release providing for the highest present worth of the net benefits over an N-year period as the outcome of 11 large loops for regulations of 90% through 40% at 5% decrements. The execution of such a run for a 12,784-day operation period (N=35) takes about five seconds in common PCs.

Although operations with regulations as low as 40% of the average inflow are executed, our models automatically release more than the target flows in any day when the active pool is top full. The assumption here is that the extra energy produced in any day will be used somehow. For example, according to a report funded by the European Union's Horizon 2020 Research and Innovation Programme, the extra electric energy can be used up for desalinization of sea water which in turn will be diverted to a nearby urban center [28]. Other plausible usages of extra energy are: extraction of oxygen and hydrogen gases by electrolysis of water, recharging of large-capacity battery fields developed in recent years to instantly counter peak demands of towns for periods of a few hours or even a couple of days. In a recent summit initiated by the European Union, a commitment for investment of large-scale electrolysis facilities for production of hydrogen has been signed by many relevant organizations including private commercial companies [29].

Our models take into account daily releases for all purposes next to energy, and they account for all of them quantitatively and detect that regulation providing for the highest present worth of financial benefits due to energy production. In short, our models realistically quantify the potential capacity of optimum energy production and the net financial gains thereof by simulating the actual hydrologic, hydraulic, and electric happenings in conjunction with the active storage capacity and its rate of change with elevation, with the rating curve of the tailwater pool, and with all the relevant peculiarities of the hydropower plant affecting the production of energy such that over an operation period of 35 or 50 years, the optimum potential is obtained as the outcome.

Concise flowcharts depicting all these phases and succinct details of our models are given in Figure 2a and Figure 2b.

3.5. Regressions for the Average Energy Production and the Optimum Financial Benefit

We have applied the steady-rate and the night-shift-pumped-storage operation simulation models to 11 dams in various regions in Türkiye. By experience (e.g. [14, 23]) we hypothesize that both the average annual produced energy and the present worth of financial benefits by marketed energy over an N-year operation period may be related to some relevant explanatory variables. In the following we are listing these variables along with the reasons for choosing them.

1) Average inflow in hm^3/year (symbolized by x_1 in the regression analyses).

Obviously, there must exist a positive relationship between the average hydroelectric energy and the average inflow coming to the reservoir.

2) Ratio of (target outflow for energy generation in hm^3/day)/(average inflow in hm^3/day), which is the regulation for a hydropower dam (symbolized by x_2 in the regression analyses).

If the total storage capacity of a dam is very large, then it can keep all of the hydrograph of an extreme incoming flood. If such a case were real, then the maximum value of the average outflow for generation of hydropower would equal the long-term average inflow. This is impossible, and even those dams having considerably large storage capacities will have to discard some portions of extreme floods over the flood spillway. Therefore, a regulation of 1.0 is impossible and it must be smaller than 1.0. Yet, it is a known fact that higher the active storage capacity higher the regulation without causing depletion of water in the active storage.

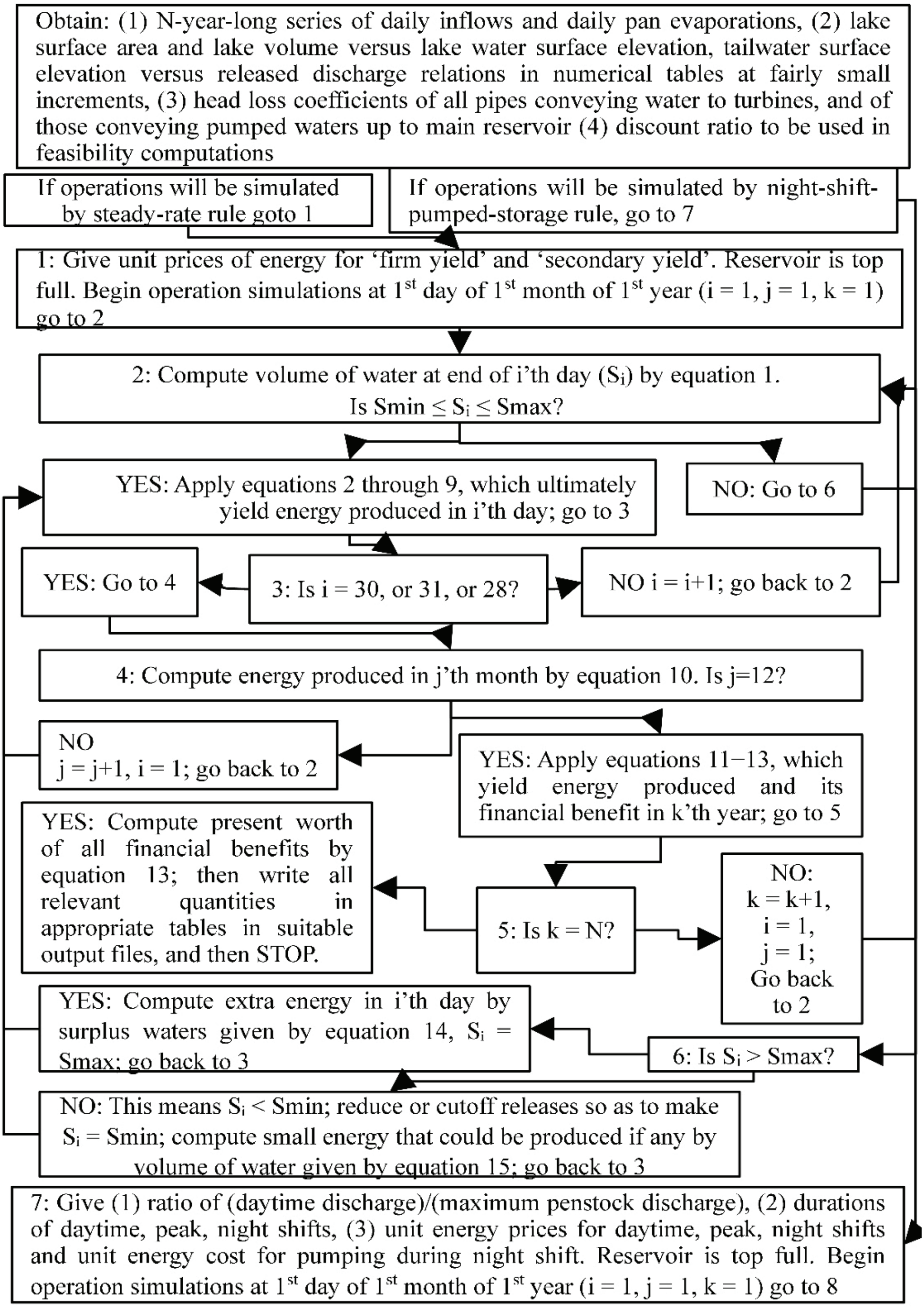

Figure 2a - Flowchart of the onset and flowchart of the model for the steady-rate rule

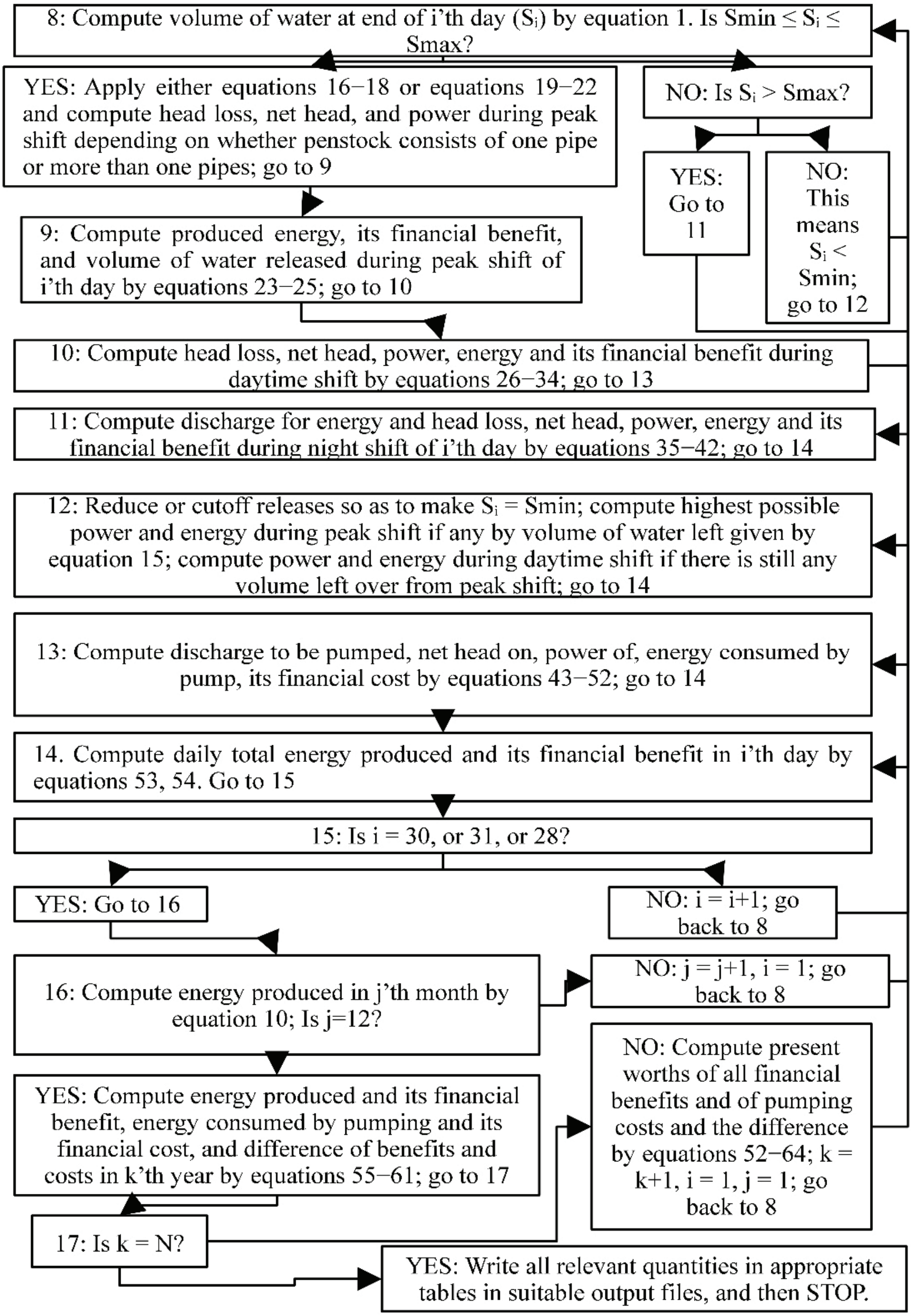

Figure 2b - Flowchart of the model for the night-shift-pumped-storage rule

3) Average net head on a turbine in m with the average target outflow for energy generation when the volume of water in the active storage is as much as half of the active storage capacity (symbolized by x_3 in the regression analyses).

Because of existence of sub-periods of droughts and of excessive flows over the total N-year operation, the water surface level fluctuates between the maximum and the minimum operation elevations. Hence, the net head on turbines when the reservoir is half full should be a realistic explanatory variable affecting the generated power and the resultant energy.

4) Ratio of (active storage capacity in hm^3)/(average inflow in hm^3/year) (symbolized by x_4 in the regression analyses).

This ratio reflects the maximum amount of storable water to be used during periods of low flow and it quantitatively describes the relative size of the active storage capacity in proportion to the average inflow. Higher this ratio higher the possible target outflow for energy generation and higher the energy production capacity should be.

5) Ratio of (maximum penstock discharge in m^3/s)/(average inflow in m^3/s) (symbolized by x_5 in the regression analyses).

Higher this ratio higher the energy production potential should be simply because a large portion of high flows will be diverted to the energy spillway instead of being discarded over the flood spillway.

6) Variation coefficient of the long series of N*365.25 daily inflows (symbolized by x_6 in the regression analyses).

This single variation coefficient of the long series of daily flows will reflect the fluctuations both in annual inflows and in seasonal flows. If the fluctuations are mild, a high average target energy outflow can be released from even small active storage capacities without going dry. Therefore, a small-magnitude variation coefficient should positively affect the average energy production.

7) Ratio of (average annual evaporation loss in hm^3/year)/(active storage capacity in hm^3).

Higher this ratio smaller the energy production potential should be because more volume of stored water will be lost without being used for power.

4. RESULTS AND DISCUSSION

One of the results is that for a dam whose active storage capacity is fairly small as compared to the average annual inflow, both the average annual produced energy and the present worth of financial benefits tend to increase towards the lowest regulation of 40%. This is because as the target release for energy gets small as compared to the average inflow, the active storage becomes top full many times during the operation period and more than the targeted discharge is released through the penstock in order to produce surplus energy using extra waters which otherwise would be discarded over the flood spillway. Yedigöze dam is a typical example for this case. On the other hand, for dams whose active storage capacity is considerably large as compared to the average annual inflow, like Yamula and Ermenek, 90% regulation or close to it yields the highest average annual produced energy. As examples to these cases, the results for Yedigöze and Yamula dams are presented in Tables 2 and 3 below. Some relevant input data of Yedigöze and Yamula dams are: Average annual inflows =

4424.7, 2123.2 hm^3/year; ratios of (active storage capacity, hm^3)/(average annual inflow, hm^3/year) = 0.068, 0.95; ratios of (maximum penstock discharge, m^3/s)/(average long-term inflow, m^3/s) = 2.71, 1.78; variation coefficients of observed daily flows over 35-year period of record = 0.797, 1.30, respectively.

Table 2 - Final parts of the output files of the runs for the operations by (a) the steady-rate and (b) the night-shift-pumped-storage rules for Yedigöze Dam

Regulation(*) (%)	**Average annual energy by steady-rate rule (GWh/year)**	**Average annual energy by night-shift-pumped-storage rule (GWh/year)**	**Average annual energy spent for pumping during NIGHT shift (GWh/year)**	**Average net head when active storage is half full (m)**
90	804.83	1014.09	390.49	82.20
85	814.93	1059.60	452.95	82.44
80	822.05	1106.64	519.76	82.67
75	830.24	1160.42	595.25	82.88
70	838.87	1211.39	655.50	83.08
65	846.86	1262.16	712.22	83.27
60	854.80	1319.38	777.46	83.44
55	863.42	1363.34	796.38	83.60
50	869.18	1344.35	740.10	83.74
45	872.01	1316.76	645.51	83.87
40	872.79	1281.71	591.42	83.99

(*): Regulation = (outflow for energy generation, hm^3/day)/(average inflow, hm^3/day)

The computer programs coded by the authors are executed to operation simulation models used the unit prices of marketed energy as: 0.04 \$/kWh by the steady-rate rule, 0.04 \$/kWh during the 11-hour-long DAYTIME shift, 0.06 \$/kWh during the 5-hour-long PEAK shift, and 0.02 \$/kWh during the 8-hour-long NIGHT shift in those days when the reservoir is overflowing by the night-shift-pumped-storage rule. In order for pumped-storage projects to be feasible, it is obvious that the unit cost of energy spent for pumping must be as low as possible as suggested by some relevant publications cited above. Therefore, the unit cost of energy used for pumping during the 8-hour-long NIGHT shift is taken as 0.02 \$/kWh, the same price for the energy we use as that we sell. The operation period is 35 years and the discount rate is 9.5% by both rules, which are officially advocated values for hydropower feasibility studies in Türkiye [27]. With these values, the present worth of financial benefits on account of marketing the produced energy minus the present worth of the costs spent for the energy used for pumping by the night-shift-pumped-storage rule has turned out to be greater than the present worth of the marketed energy by the steady-rate rule. Table 4 presents the maximum values of the net financial benefits by both operation rules for all of 11 dams. As seen in this table, the night-shift-pumped-storage operation turns out to be financially more profitable for all of the analyzed dams, and the average increase in net profit is 28%.

Table 3 - Final parts of the output files of the runs for the operations by (a) the steady-rate and (b) the night-shift-pumped-storage rules for Yamula Dam

Regulation(*) (%)	**Average annual energy by steady-rate rule (GWh/year)**	**Average annual energy by night-shift-pumped-storage rule (GWh/year)**	**Average annual energy spent for pumping during NIGHT shift (GWh/year)**	**Average net head when active storage is half full (m)**
90	421.67	429.75	27.94	90.88
85	428.01	456.75	60.46	91.03
80	421.42	470.20	91.70	91.17
75	412.30	480.71	122.45	91.30
70	403.06	490.13	152.48	91.42
65	394.49	498.93	181.65	91.54
60	385.95	507.12	209.61	91.65
55	379.07	514.21	235.67	91.74
50	373.48	521.09	259.90	91.83
45	368.42	526.87	281.24	91.92
40	364.16	531.33	298.13	91.99

(*): Regulation = (outflow for energy generation, hm^3/day)/(average inflow, hm^3/day)

An ultimate goal of this study has been to obtain meaningful regression equations depicting the average annual produced energy in terms of a few explanatory variables given in the previous section. For the regression analyses we used the package program Minitab [30]. In the following, only the regression equations including the significant explanatory variables are presented, and the details like ANOVA (analysis of variance) tables are skipped in order not to extend the length of the paper.

Table 4 - Maximums of present worths of net financial benefits on account of marketing the energy produced by the operation rules of (a) the steady-rate and (b) the night-shift-pumped-storage for all of 11 dams studied (Operation period = 35 years, discount ratio = 0.095, unit prices of marketed energy are: 0.04 \$/kWh for steady-rate rule, 0.04 \$/kWh during 11-hour-long DAYTIME, 0.06 \$/kWh during 5-hour-long PEAK shifts, and 0.02 \$/kWh produced during 8-hour-long NIGHT shift in those days when the reservoirs is overflowing; unit cost of energy used for pumping during 8-hour-long NIGHT shift is: 0.02 \$/kWh. Operations are simulated in daily time steps).

Dam	**Maximum present worth (PW) by steady-rate rule (Million Dollars)**	**Maximum of difference of PW of benefits minus PW of pumping costs by night-shift-pumped-storage rule (Million Dollars)**	**Relative Difference (Percent)**
Ağaçhisar	33.68	39.68	+18%
Altınkaya	636.71	972.94	+53%
Bahçelik	8.43	10.74	+27%
Berdan	44.26	48.57	+10%
Ermenek	469.88	568.43	+21%
Hasan Uğurlu	603.88	797.02	+32%
Karakurt	132.48	174.81	+32%
Kılıçkaya	170.83	216.73	+27%
Susurluk	28.63	37.89	+32%
Yamula	173.44	202.15	+17%
Yedigöze	380.49	516.15	+37%

Average relative difference = +28%

$$AESR = (-418.3) + (0.2112)*x_1 + (2.834)*x_3 + (78.01)*x_4 + (124.9)*x_5 + (-149.5)*x_6 \quad (65)$$

Degree of freedom = 121 − 6 = 115, R^2_{adj} (adjusted determination coefficient) = 0.985

t values of the coefficients of this regression equation and their significance probabilities: −418.3, −10.7, 100%; 0.2112, 48.1, 100%; 2.834, 26.5, 100%, 78.01, 3.00, 99.7%; 124.9, 11.7, 100%; −149.5, −7.21, 100%

$$AENSPS = (-973.7) + (0.3509)*x_1 + (4.635)*x_3 + (330.5)*x_5 + (-277.2)*x_6 \quad (66)$$

Degree of freedom = 121 − 5 = 116, $R^2_{adj} = 0.954$

t values of the coefficients of this regression equation and their significance probabilities:

−973.7, −8.21, 100%; 0.3509, 27.9, 100%; 4.635, 20.8, 100%, 330.5, 10.1, 100%;

−277.2, −4.38, 100%

$$PWSR = (-146.5) + (0.08525)*x_1 + (1.297)*x_3 + (46.82)*x_5 + (-67.22)*x_6 \quad (67)$$

Degree of freedom = 121 − 5 = 116, $R^2_{adj} = 0.989$

t values of the coefficients of this regression equation and their significance probabilities:

−146.5, −10.8, 100%; 0.08525, 59.4, 100%; 1.297, 50.8, 100%, 46.82, 12.5, 100%;

−67.22, −9.30, 100%

$$PWNSPS = (-268.0) + (0.1215)*x_1 + (1.619)*x_3 + (89.05)*x_5 + (-94.57)*x_6 \quad (68)$$

Degree of freedom = 121 − 5 = 116, $R^2_{adj} = 0.981$

t values of the coefficients of this regression equation and their significance probabilities:

−268.0, −10.6, 100%; 0.1215, 45.2, 100%; 1.619, 33.9, 100%, 89.05, 12.7, 100%;

−94.57, −6.99, 100%

In these equations, the variables are: AESR: average annual energy produced by the steady-rate rule in GWh/year, AENSPS: average annual energy produced by the night-shift-pumped-storage rule in GWh/year, PWSR: present worth of financial benefits due to marketed energy at the beginning of a 35-year operation period by the steady-rate rule in $'s, PWNSPS: present worth of financial benefits due to marketed energy at the beginning of a 35-year operation period by the night-shift-pumped-storage rule in $'s, the explanatory variables x_i's are as explained before; and, the coefficients of the explanatory variables all are significant with a probability greater than 99.8% as given by the Confidence Intervals based on the Student's t test. Figures 3 and 4 show the scatter plots of average annual energy produced versus average annual inflow and the ratio of (maximum penstock discharge)/(average inflow) by the steady-rate rule and Figures 5 and 6 show the same plots by the night-shift-pumped-storage rule. The other graphs are not included in order to save space from the length of the paper.

The regression equations presented for the average annual energy produced by either the steady-rate or the night-shift-pumped-storage rule should be valid for a realistic initial estimate everywhere, while those for the present worth of financial benefits are specific for conditions used here. For example, the results of the night-shift-pumped-storage rule depend on the assumption that the target release for energy during the 11-hour-long DAYTIME shift equals 70% of the maximum penstock discharge capacity. Yet, the coded programs are flexible and they will run for any operation periods, for any unit energy prices and unit pumping costs, for any discount ratios, for any durations of the three shifts, and for any DAYTIME penstock discharge ratios within the boundaries of inequality (27).

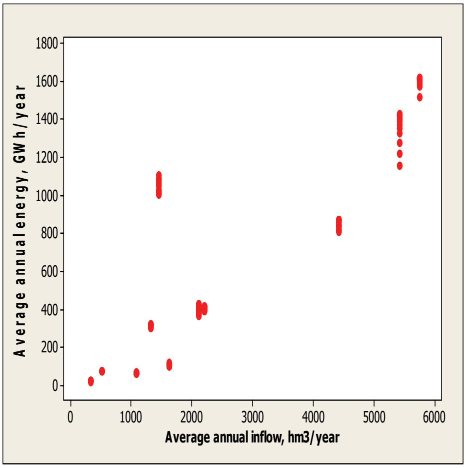

Figure 3 - Scatter plot of average annual energy versus average annual inflow for all 11 dams by the steady-rate rule

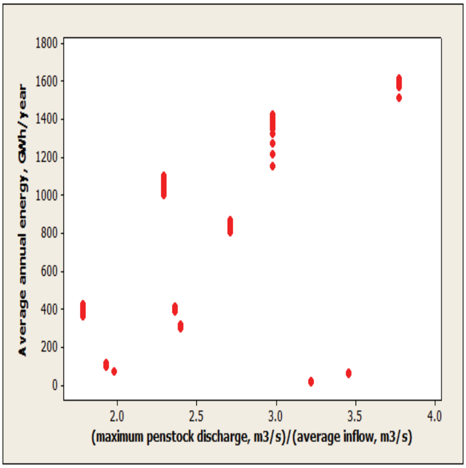

Figure 4 - Scatter plot of average annual energy versus ratio of (maximum penstock discharge) to (average inflow) for all 11 dams by the steady-rate rule

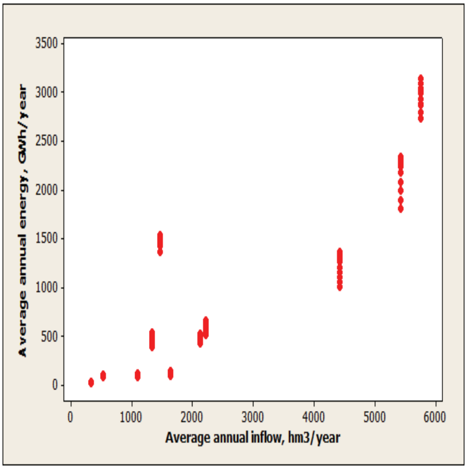

Figure 5 - Scatter plot of average annual energy versus average annual inflow for all 11 dams by the night-shift-pumped-storage rule

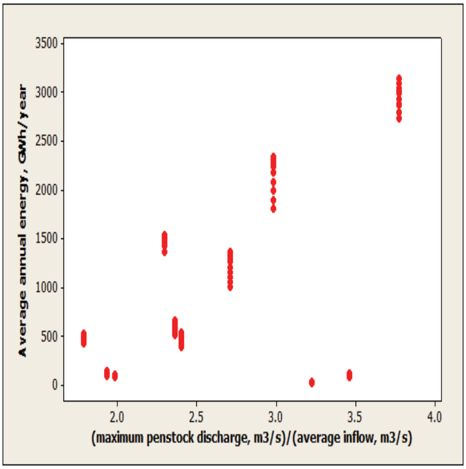

Figure 6 - Scatter plot of average annual energy versus ratio of (maximum penstock discharge) to (average inflow) for all 11 dams by the night-shift-pumped-storage rule

5. CONCLUSIONS

The technical details given in the final design projects of the selected dams are taken as the material of this study. Most of these dams are on unregulated streams. For only a couple of these dams, there are other dams at upstream locations quite far away. For example, Hirfanlı Dam is located on Kızılırmak River about 200 km upstream from Altınkaya Dam. So, the regulation effect of those upstream reservoirs on stream flows will be minimal.

After having applied our operation simulation models in daily time steps to these 11 dams, we have carried out the multiple regression analysis which we have summarized in the preceding section. It is impractical and almost impossible (1) to acquire or calculate the daily 35-year-long stream flow series coming to the dam, (2) to obtain the design projects, (3) to extract the necessary data from the project documents and prepare the input data files, (4) to execute the runs, and (5) to deduce the generalized relationships on all dams in the world with hydropower plants. However, as put forth in the previous section, we have still obtained statistically highly meaningful regression equations as the outcome of applying our models on these 11 dams. These particular dams have wide ranges of storage capacities, installed powers, and average stream flows. The ranges of active storage capacities, of ratios of (active storage capacity)/(average annual inflow), of net heads on the turbines when the volume of water in the active storage is as much as half of its capacity, and of ratios of (maximum penstock discharge)/(average inflow) of these 11 dams are: 80 hm^3 ~ 2900 hm^3, 0.07 ~ 1.20, 19 m ~ 342 m, 1.8 ~ 3.8, respectively. Hence, the regression equations obtained using the results of these dams cover such wide ranges, and therefore, these equations can be used for a plausible and reasonable prediction of hydroelectric energy potential of prospective projects.

For the night-shift-pumped-storage operation, the hydropower plant is running at maximum turbines capacity during the PEAK shift and it is running at 70% capacity during the DAYTIME shift. Yet, any value for this ratio between the lower bound given by expression (27) and 100% can be assigned by the program user. The turbines can be operated at full capacity during the DAYTIME shift also provided that the pumping capacity during the 8-hour NIGHT shift is large enough to pump back the volume of water equalling the full penstock discharge over a 16-hour period minus the target release further downstream from the tailwater reservoir. Because the computer programs are user-friendly and the execution time of a run takes about five seconds, sensitivity analyses with different DAYTIME penstock discharges, with different unit energy prices, with different discount rates, and with different operation periods can easily be done for any dam.

It has been shown that there are net positive relative financial benefits, varying between 10% and 50%, by the night-shift-pumped-storage rule over the conventional rule of steady-rate for all those 11 dams analyzed in this study. Since as of now, none of these dams are capable of pumping, for the conversion of them to the night-shift-pumped-storage rule, the cost of either installing a motor/pump unit or replacing the existing turbine/generator unit by a reversible (turbine/generator)↔(motor/pump) system must be smaller than the net financial benefits. The models and the coded programs provided can help the authorities to make feasible decisions about such possible conversions.

The models and the computer codes developed and presented in this study for the simulation of the operation of a dam with a hydropower plant either by the steady-rate or by the night-shift-pumped-storage rules in daily steps and involve novelties and precise details peculiar to themselves. These codes, which are free to anybody interested, make up the major contribution of this study. The statistically significant regression equations obtained for a reasonable estimate of the annual average produced hydroelectric energy either by the steady-rate or by the night-shift-pumped-storage rules can also be mentioned as another contribution.

References

[1] IHA (2018) *The world's water battery: Pumped hydropower storage and the clean energy transition*. International Hydropower Association. www.hydropower.org/publications/

[2] Zhang S, Andrews-Speed P, Perera P (2015) The evolving policy regime for pumped storage hydroelectricity in China: A key support for low carbon energy. *Applied Energy*, 150, 15–24. http://dx.doi.org/10.1016/j.apenergy.2015.03.103

[3] Uria-Martinez R, Johnson M M, Shan R (2021) U.S. *Hydropower Market Report*. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Water Power Technologies Office, USA. http://www.osti.gov/bridge

[4] Gimeno-Gutierrez M and Lacal-Arantegui R (2015) Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. *Renewable Energy*, 75, 856–868. http://dx.doi.org/10.1016/j.renene.2014.10.068

[5] DSI (2022) *General Activities Report of the Year 2021* (in Turkish). General Directorate of State Hydraulic Works, Ministry of Forestry and Water Works of Republic of Türkiye, Ankara, Türkiye.

[6] Ak M, Kentel E, Savasaneril E (2019) Quantifying the Revenue Gain of Operating a Cascade Hydropower Plant System as a Pumped-Storage Hydropower System. *Renewable Energy*. DOI: 10.1016/j.renene.2019.02.118

[7] Aydemir A, Acanal N, Haktanir T (2019) Efficient Use of Renewable Energy Sources: Pumped Storage Hydroelectric Power Plants. In E. Hüseyin & A. Nurlan (Eds.), *3rd International GAP Congress on Mathematical-Engineering-Technical-Medical Sciences, Proceedings,* 917–923. https://www.gapzirvesi.org/

[8] Aydemir A and Haktanir T (2019) Integration of Pumped Storage Hydropower Plant to Çamlıgöze Dam. *Internationally Participated The 1st Innovation, Sustainability, Technology and Education in Civil Engineering Conference*, *Proceedings,* 640–651. http://iste-ce2019.iste.edu.tr/

[9] Ayder E (2015) *Pumped Storage Hydroelectric Power Plants, Technical Report* (by Prof. Dr. Erkan Ayder) (In Turkish) Mechanical Engineering Department, Istanbul Technical University, Istanbul, Türkiye.

[10] Bozdemir M (2013) *Evaluation and Analysis of Pumped-Storage Hydroelectric Plants for Türkiye* (In Turkish). M.Sc. Thesis, Bilecik Seyh Edebali University, Graduate School of Sciences, Electrical and Electronics Engineering Program, Bilecik, Türkiye.

[11] Cicek O and Ozdemir M B (2021) Pumped Storage Hydroelectric Power Plant Design. *Gazi Journal of Engineering Sciences*, 7(1), 26-35. https://dx.doi.org/10.30855/gmbd.2021.01.04

[12] EIE (2008) *Elektrik İşleri Etüt İdaresi Genel Müdürlüğü İlk Etüt Raporları, 2008* (In Turkish). General Directorate of Electrical Works Planning and Reconnaissance, Ankara, Türkiye. http://www.eie.gov.tr/

[13] Firis F A, Karadol I, Sekkeli M (2022) Investigation of Unit Commitment Problem in Presence of Pumped Storage Hydroelectric Power Plants: The Case of Kahramanmaras. *Gazi Journal of Engineering Sciences*, 8(1), 110−121, doi:10.30855/gmbd.2022.01.10

[14] Haktanir T, Aydemir A, Acanal N (2021) A study on three different hydropower operation rules by monthly and daily time steps. *Proceedings of the Institution of Civil Engineers – Energy*, 174(1) 24−34. https://doi.org/10.1680/jener.19.00066

[15] Karacay P (2010) *Pumped Storage Power Plants and Their Status in Türkiye* (In Turkish). M.Sc. Thesis, Istanbul Technical University, Graduate School of Sciences, Civil Engineering Department, Hydraulics and Water Resources Program, Istanbul, Türkiye.

[16] Unver U, Bilgin H, Guven A (2015) Pumped-Storage Hydroelectric Systems (In Turkish). *Mühendis ve Makina* (A national journal in Turkish), 56(663), 57−64.

[17] Yenerji (2014) *The Project of Karakurt Dam and Hydropower Plant Revised Feasibility Report* (in Turkish) Yenerji Engineering and Consulting Co., Ankara, Türkiye, www.yenerji.com.tr

[18] USACE (1985) *Engineering and Design HYDROPOWER, EM 1110-2-1701*. U.S. Army Corps of Engineers, Washington, DC, 20314-1000.

[19] Sever S and Yurtal R (2022) Simulation of Multi-Purpose Multi-Reservoir System Operations by HEC-ResSim (In Turkish) *Teknik Dergi*, Paper 708, 12863-12875.

[20] Haktanir T, Aydemir A, Acanal N Versions of the drainage area ratio method for transfer of daily or monthly stream flows. *Proceedings of the Institution of Civil Engineers – Water Management*, https://doi.org/10.1680/jwama.21.00091, ahead of print.

[21] Openstreet, Openstreet map database 2022, Available under the Open Database Licence from: https://www.openstreetmap.org/copyright, accessed 10.09.2022

[22] HGM, General Directory of Mapping, Republic of Türkiye, Ministry of National Defense, Türkiye shape file: https://www.harita.gov.tr/urun/turkiye-mulki-idare-sinirlari/232, accessed 10.09.2022

[23] Haktanir T and Cobaner M (2007) Feasibility of hydropower plant installation to existing irrigation dams. *Water International*, IWRA, 32(2), 254–264. https://doi.org/10.1080/02508060708692205

[24] Elliott T C, Chen K, Swanekamp R C (1998) *Standard Handbook of Power Plant Engineering*, Section 7. Hydroelectric Power Stations, Second Edition. McGraw-Hill, New York.

[25] Coyne et Bellier (1986) *Sir Dam and Hydroelectric Project, Water Potential and Power Studies (Revision)*. Coyne et Bellier, Bureau d'Ingenieurs Conseils, Paris, France, Aknil Engineers Consultants, Ankara, Cukurova Elektrik A.Ş., Adana, Türkiye.

[26] Gulliver J S and Arndt R E A (1991) *Hydropower Engineering Handbook*. McGraw-Hill.

[27] DSI (2015) *Circular 2015/5 Criteria for Reconnaissance and Feasibility Studies* (in Turkish). Investigation, Planning and Allocations Department, General Directorate of State Hydraulic Works, Ministry of Forestry and Water Works of Republic of Türkiye, Ankara, Türkiye.

[28] Hydropower Europe (2019) *Hydropower Technologies The State-of-the-Art*. Document No. WP4-DIRp-02, Lead author: Emiliano Corà, Contributors: Jean Jacques Fry, Mario Bachhiesl, Anton Schleiss. A technical report prepared under grant agreement No 826010 supported by the European Union's Horizon 2020 research and innovation programme.

[29] European Clean Energy Alliance (2022) *Joint Declaration European Electrolyser Summit V9 public*. European Commission, Hydrogen Europe, Advent, Bosch, Convion, Cummins, DeNora, Elogen, Enapter, Genvia, Green Hydrogen Systems, Hydrogen & Energy Systems, H2B2, HyStar, John Cockerill, McPhy, NEL Hydrogen, Siemens Energy, Solid Power, Sunfire, Thyssenkrupp nucera, Topsoe, Brussels, 5 May 2022.

[30] Minitab: Data Analysis, Statistical & Process Improvement Tools, www.minitab.com Minitab, LLC 1829 Pine Hall Road, State College, PA, USA.