A SIMPLIFIED EXAMPLE TO UPGRADING OF A HYDROPOWER PLANT THROUGH RE-EQUIPMENT AND EXTENSION WITH A PUMP-HYDRO-STORAGE-UNITE

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Abstract: It is known that hydropower is one of the most reliable and proven sources of generating electricity, with three important attributes: it is renewable, available on demand, and it can be used to store power. But the normal life expectancy of a hydroelectric power plant is only 30 to 35 years and consequently renovation and usually upgrading is required thereafter at the end of this period. In the present paper a briefly calculation example to efficiency analysis of upgrade and modernization of a hydropower plant as well his extension with a pump-hydro-energy-storage- unite. This can be an aid as orientation basis for the elaboration of some preliminary studies to updating of existing waterpower plant.
Keywords: hydropower upgrading, pump-hydro-storage, energy and economic efficiency

1. INTRODUCTION

According to Hydropower Status Report 2020 of International Hydropower Association the hydropower installed capacity reached 1,308 gigawatts (GW) in 2019 and will be grow by around 60 per cent by 2050. Electricity generation from hydropower hit a record 4,306 terawatt hours, the single greatest contribution from a renewable energy source in history [1]. But, it is worth mentioning that in the future additional capacities will be less realized through building new hydropower plants, but mainly through upgrade and modernize of existing capacities hydro power plants older than 30 years meanwhile about 600 GW. That especially in Europe where subject to serious environmental restrictions for new hydropower plant. As well pumped storage capacity should more than double because this growth is vital to support variable renewable energy.

Hydropower is one of the most reliable and proven sources of generating electricity, with three important attributes: it is renewable, available on demand, and it can be used to store power [2]. Most hydro plants use advanced technology economically available at the time they are built. But knowing that the normal life expectancy of a hydroelectric power plant is only 30 to 35 years a renovation and usually

upgrading is planned thereafter at the end of this period. [2], [3], [4].

Modernization of a hydropower plant is an extremely complex issue and require a structured analysing process beginning with the assessing the actual state of the plant to evaluating the most appropriate, feasible and economic solutions [5].

In this regard in the present paper a simplified calculation example to technical-economic efficiency analysis the upgrading and modernization of a Hydro-power plant (HPP) through re-equipment and extension with a new pump-hydro-energy-storage-unit (PHS). We consider that this calculation example can be useful as basis for the elaboration of some preliminary studies for planning and decision making for upgrading and modernization of an aging waterpower plant.

The presented example contains hydraulic calculations considering the updated discharge hydrograph and consists mainly of:

• Determination of the annual mean discharge (Q_M in m3/s), which is the total installed discharge for 3 turbines of the HPP. Consequently, the installed discharge of a turbine is $Q_T = Q_M / 3$.

• Calculation and representation of the cumulative discharge curve (i.e., cumulative discharge volume curve) using the given discharge hydrograph

• Checking the required water volume which must be stored in the existing reservoir using the updated discharge hydrograph and comparing him with the available volume from a topographic point of view and find out whether if there is enough volume reserve for an extension of the system with a new pump-hydro-energy-storage unit (PHS).

• Calculation the installed power of the turbines and the annual energy potential of the hydropower plant considering an overall efficiency (turbine, generator) of 80-90%.

• Selection the three new suitable turbine-type corresponding to the calculated discharge Q_T and to the given fall height h of a hydropower

• Assessment the economic efficiency of the hydropower plant using the amortizations period of the investment (with and without credit) considering

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the investment costs, operating cost, and revenue from electricity sales.

For carrying out the above-mentioned calculations the following *data are required as given data:*

• The multiannual averaged monthly discharge (Table 1)

Table 1

Months	Monthly discharge Q_{mo} [Million m³ / month]	Monthly discharge [m³ / s]
1	70	27,0
2	251	96,8
3	269	103,8
4	479	184,8
5	675	260,4
6	1019	393,1
7	36	13,9
8	1023	394,7
9	213	82,2
10	45	17,4
11	88	34,0
12	47	18,1
∑	**4215**	**1626,2**
Ø	**351,3**	**135,5**

By graphical representation, the discharge hydrograph is obtained corresponding to the multiannual averaged monthly discharge (Figure 1).
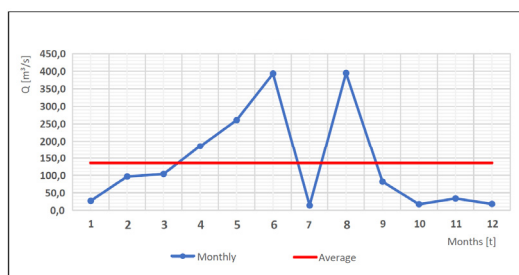

Figure 1. Discharge hydrograph

• The considered averaged fall height of a hydropower is h = 95m

• The upgraded waterpower plant is provided with 3 new turbine-units, each with a discharge of $Q_T = Q_M / 3$ ($Q_M \triangleq 136m^3$ /s denotes the multiannual averaged discharge see Table 1)

• The maximal possible water volume which can be accumulated from topographical point of view with the current dam without rehabilitation measures is 2 Million mc.

The rehabilitated hydro power plant with three new turbines will be extended whit a new pump-hydro-energy-storage (PHS) unit with an installed discharge of $Q_{PHS}=Q_T/2 =Q_M/6 \triangleq 23m^3$/s and the same fall high of h=95m.

The hydraulic calculations follow the methodology used in [7]. The cost estimations are based on the summarizing data contained in the experience report in accordance with Section 97 of the Renewable Energy Sources Act, Germany, and generally in Europe [8], [9], [10]. For example, among others the investment costs for a HPP greater than 100 kW installed power vary within € 2000/kW to € 8000/kW [6], [8] which agree relatively well with those in USA where, according to Market Report

2018 prepared for U.S.A. Department of Energy Water Power Technologies Office (capital costs of recently developed hydropower plants vary within a range of $2000 to $8000 per kilowatt installed).

In the next two paragraphs some hydraulically and economical calculations regarding to upgrading of a HPP and his extension with a PHS unit will be presented.

2. HYDRAULIC AND ECONOMIC CALCULTIONS OF UPGRADED HPP

2.1 Some Hydraulic calculations of HPP

The first calculation refers to check of the *required storage volume* in the existing lake corresponding to the updated hydrological data.

In this regard the given updated monthly discharge values (Table 1) depicted also in Figure 1 as discharge hydrograph will be used. Using these data, the cumulative volumes of the monthly discharges Q_{mo} as well the cumulative volumes of the annual averaged monthly discharge of $Q_M \triangleq 136m^3$/s

are calculated (Table 2 and Figure 2).

Table 2 cumulative discharge volumes

Months	Cumulative volume of monthly discharge [Million m³]	Cumulative volume of annual averaged monthly discharge [Million m³]	Volume difference between both discharges [Million m³]
1	70	351,25	-281,25
2	321	702,5	-381,5
3	590	1053,75	**-463,75**
4	1069	1405	-336
5	1744	1756,25	-12,25
6	2763	2107,5	655,5
7	2799	2458,75	340,25
8	3822	2810	**1012**
9	4035	3161,25	873,75
10	4080	3512,5	567,5
11	4168	3863,75	304,25
12	**4215**	**4215**	0

The required storage capacity V_{SC} of the reservoir is calculated by adding the amounts of the minimum value (ΔV1= -464 Mill. m³) and maximum value (ΔV2=1.012 m³) of the difference between cumulative monthly discharge and cumulative annual averaged discharge (Table 2 and Figure 2) is:

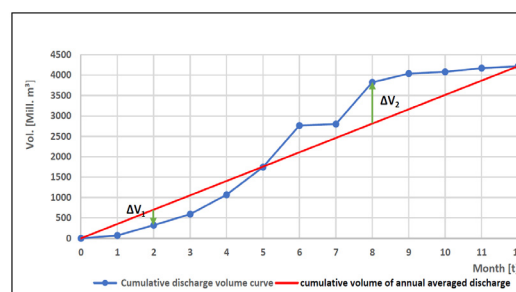$$V_{SC} = |\,\Delta V1\,| + |\,\Delta V2\,| = 464 + 1.012 = 1.476 \text{ Mill } m^3.$$

Figure 2. Cumulative discharge volumes

Comparing with the existing volume of two million m³ can see that about a half million m³ are still common which can be used for the establishment of the new PHES-unit.

24

The next step is the calculation of **installed power** of the turbines and the *selection of the appropriate turbine type.*

The installed power is expressed with the following relation:

$$P_T = \eta * \rho * g * Q_T * \qquad (1)$$

η_T is the overall efficiency coefficient, ρ *is the* water density, Q_T is the discharge of the turbine and h is the fall head.

Using the available data i.e., fall head $h = 95$ m and annual average monthly discharge $Q_T = Q_M / 3 \triangleq 45$ m^3/s the power of the turbine can be calculate. Considering an efficiency coefficient of $\eta = 0.95$ and knowing the water density $\rho = 1.000$ kg / m^3, the gravitational acceleration $g = 9,81$ m / s^2 the power of a turbine is:
$P_T = \eta * \rho * g * Q * \quad = 0.95 * 1.000 * 9,81 * 45 * 95 \triangleq 40$ MW.

Consequently, the installed power of the entire HPP with three turbines is $P_{HPP}=120MW$.

Using the turbine application chart (Figure 3), it can see that for $Q_T=45$ m^3/s and $h=95m$ the Francis turbine type is appropriate.
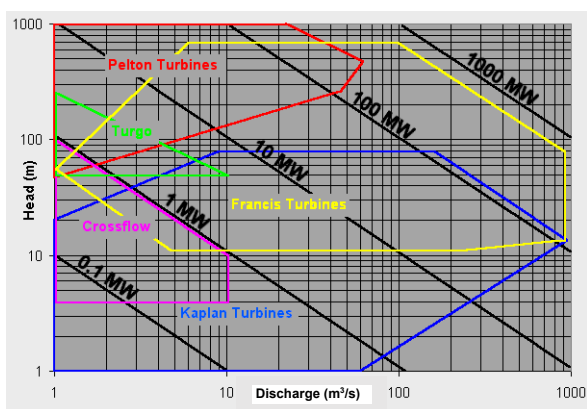

Figure 3. Turbine application chart, net fall head *h* versus discharge Q_T [6]

The *annual energy production* of the hydropower plant (E_{HP}) considering a full load of t_{fl} hour pro year (from 8,760 h / year) is:

$$E_{HP} = P * t_{fl} = \eta * \rho * g * Q_T * \quad * t_{fl} \quad (2)$$

For the considered example, the *annual energy production* of the hydropower plant (E_{HP}) with a full load hour of $t_{fl} =6.000$ h/a is:
$E_{HP} = P * t_{fl} = 120 * 6.000 = 720$ GWh/ a

2.2 Evaluation of the economic efficiency of HPP

The amortization period in years (t_A) is an of the appropriate criterion for the assessment of economic efficiency of an HPP.
a) Estimation of the amortization period without financing through a loan

It will be considered the static amortization period (t_A *in years*) defined by dividing the investment costs for modernization *(I_C in €*) by the annual cost saving obtained from delivered electricity (E_C *in €/a*) minus operating costs (O_C *in €/a*):

$$t_{Am} = \frac{I_C}{E_C - O_C} \qquad (3)$$

To calculate the amortization period (t_A) using formula (3) the parameters I_C, E_C and O_C should be determined.
-Estimation of the investment costs (I_C):
Noting the specific investment costs (in *€ / kW*) with C_{spT} for turbine, C_{spG} for generator, C_{spTr} for transmissions and with C_{spCs} for control system the total investment costs for the PHS can be expressed as:

$$I_C = P * (C_{spT} + C_{spG} + C_{spTr} + C_{spCs}) \qquad (4)$$

For the installed power of $P = 120$ MW of the HPP and considering the specific investment cost [5], [6]:
C_{sp}-*Turbine = 1.980 € / kW*
C_{sp}-*Generator = 760 € / kW*
C_{spT}-*Transmissions = 2.300 € / kW*
C_{sp}-*Control system = 750 € / kW*
Replacing the numerical values in (4) we obtain the *investment costs* for the upgrading of the HPP:
$I_C \triangleq 695 \cdot 10^6$ *€*
-Estimation of the operating costs (O_C):
The operating costs are calculated using the specific operating cost of *13 € / kW* installed power indicated for upgrading and modernization of HPP [5], [6], [7]: $O_C=120 \cdot 10^3 \cdot 13 \triangleq 1,56 \cdot 10^6$ *€/a*
-Estimation of the cost saving obtained from delivered electricity (E_C):
The cost saving obtained from delivered electricity (i.e., income) depend on the installed capacity of the HPP. For an installed capacity of 50 MW or more the specific payment is 3,48 ct/kWh $\triangleq$ 0,04 € / kWh [5], [6], [7]. For the considered HPP with annual energy production of $E_{HP} \triangleq 720$ GWh/y the annual cost saving is: $E_C=720 \cdot 10^6 \cdot 0,038 \triangleq 27,9 \cdot 10^6$ € /a.

The amortization period t_{Am} of the HPP without financing through a loan obtain using formula (3) in which the above estimated costs replace obtain:

$$t_{Am} = \frac{I_C}{E_C - O_C} = \frac{695}{27,9 - 1,55} \cong 26 \text{ years}$$
(3*)

b) Estimation of the amortization period with financing through a loan
If the modernization measures are financed through a loan the costs per year are determined under the assumption that the duration of the loan either corresponds to the lifetime of the measure or to a general recommendation/specification. Often, this is said to be 20-30 years [10].
Considering financing the calculation formula of the amortization period is

$$t_{Am} = \frac{n \cdot R_a}{E_C - O_C} \qquad (5)$$

25

R_a, the total annual costs of the measure (in €/a) = investment costs I_C (in €) multiplied with the annuity factor $A_{n,i}$ (in 1/a):

$$R_a = I_C \cdot A_{ni} \qquad (6)$$

The annuity factor $A_{n,i}$ can be determined knowing the interest rate i (%) and duration n (y) using the formula:

$$A_{n,i} = \frac{(1+i)^{n-1} i}{(1+i)^n - 1} \qquad (7)$$

Assuming a loan amount identically with the investment costs I_C and an interest rate of $i = 3\%$ and a term of repayment of $n = 20$ years we obtain using (7) an annuity factor of $A_{n,i}=0,065$. Knowing $A_{n,i}$ and I_C result from (6) $R_a=44,85$. Considering E_C and O_C calculated above and using formula (5) the resulted amortization period is $t_A \triangleq 34$ years.

It is to mentions that the obtained amortization periods of $t_A \triangleq 26$ years without loan and $t_A \triangleq 34y$ with loan respectively satisfied the essential requirement of an investment for upgraded measures of a HPP which must be less than his technical lifetime of about 35 years [4], [5], [6].

3. EEXTENSION OF HPP WITH A PUMP-HYDRO-STORAGE-UNITE

The upgraded HPP will be with an additional pump-storage-unit (PHS) extended. The following data are considered given data for the extension:
• The assumed installed flow rate for the turbine of the additional PHSP is: $Q_{T-PHS} = 0.5Q_T \triangleq 23$ m^3/s
• The operating time of the PSKW is around 300 days in a year with daily averaged turbine operating time of $t_{tT} = 6$ h / day and a pump operating time of $t_{tP} = 12$ h / day, respectively.
• The reservoir of the existing HPP (Chapter 2) is also used as upper reservoir for the PHS, assuming that the volume of the reservoir is large enough that the influence of the fluctuating operation on the fall head h can be neglected (i.e., the fall head h of 95 m remains practically unchanged)
• The lower reservoir will be newly set up and there are convenient conditions for its arrangement with relatively cheap costs of about 20 $€/m^3$
• The fall head and the pump head are approximately the same $h_{P-PHS} \approx h_{T-PHS} =95m$ (hydraulic head losses I system are neglected)
• The specific cost of electricity at basic load is about 20 €/MWh while 70-100 €/MWh at peak load

The hydraulically and efficiency calculations consisting mainly of:
• Calculation of the averaged discharge of the pump (Q_P) considering the given operating time of the turbine and of the pump and considering the same daily operated water volume for both pump and turbine, respectively.
• Calculation of the required volume of the lower reservoir according to the installed flow rate of the PHSP

• Estimation of the investment costs
• Estimation of the pump operating costs
• Estimation of the cost saving (incomes) obtained from delivered electricity by peak load
• Calculation of the amortization period t_{Am}

3.1 Some hydraulic calculations to PHS

Th discharge of the pump (Q_P) can be calculated considering the given operating time of the turbine of $t_{tT} = 6$ h / day and the given pump operating time of $t_{tP} = 12$ h / day with the assumption that baths turbine and pump have the same daily operation volume (i.e., $Q_P \cdot t_{tP} = Q_{TPHS} \cdot t_{tT}$) and knowing the turbine discharge $Q_{TPHSP} \triangleq 23$ m^3/s results $Q_P = 0.5Q_{TPHSP}=11,5$ m^3/s.

The required storage volume V_{sr} of the lower reservoir according to the installed turbine discharge of the PHSP of $Q_{T-PHS} \triangleq 23$ m^3/s and operating time of $t_{tT} = 6$ h / day is $V_{sr} \triangleq 500.000$ m^3.

Installed power of the PHS
Using the notations: η_T turbine efficiency coefficient, ρ water density, g gravitational acceleration, Q_{TPHSP} discharge of the turbine, h fall head the power of PHS turbine can be expressed as:

$$P_{T-PHS} = \eta_T * \rho * g * Q_{TPHSP} * _T \qquad (8)$$

Considering the numerical values of the parameter:
$\eta_T = 0.95$, $\rho = 1.000$ kg / m^3, $g = 9,81$ m / s^2, $Q_{TPHS} \triangleq 23$ m^3 / s, $h = 95$ m and using the hydropower formula (7) the installed power of the PHS turbine is:
$P_{T-PHS} = 0,95 * 1.000 * 9,81 * 23 * 95 \triangleq 20$ MW

The annual electricity production of the PHS
Through turbine operation of the PHS during the annual load hours of t_{Tl} the electricity production is:

$$E_{T-PHS} = P_{T-PHS} * t_{Tl} = \eta_T * \rho * g * Q_{T-PHS} * _T * t_{Tl} \qquad (9)$$

Replacing the numerical values of the parameter and considering the operating time of t_{Tl} $=300d \cdot 6h/d=1.800h/$a the annual energy production of the PHS on obtain: $E_{T-HSP}=20$ $MW*1.800h/a \triangleq 36$ GWh/a.

The installed power for the pump of the PHS
Considering the characteristic parameter of the pump: η_P efficiency coefficient, ρ water density, g gravitational acceleration, Q_{P-PHS} pump discharge, fall head h the calculation formula of the installed pump is expressed as follow:

$$P_{P-PHS} = 1/\eta_P * \rho * g * Q_{P-PHS} * _P \qquad (10)$$

For the numerical values of the parameter: $\eta_P = 0.8$, $\rho = 1.000$ kg / m^3, $g = 9,81$ m / s^2, $Q_{P-PHS} \triangleq 11,5$ m^3 / s, $h = 95$ m the installed power of the PHS pump is:
$P_{P-PHS} = 1/0,8 * 1.000 * 9,81 * 11,5 * 95 \triangleq 13,4$ MW

The annual electricity for the pump operation corresponding to the annual pump operation hours of t_{Pl} is expressed as:

$$E_{P\text{-}PHS} = P_{P\text{-}PHS} * t_{Pl} = \\ = 1/\eta_P * \rho * g * Q_{P\text{-}PHS} * \quad_P * t_{Pl} \qquad (11)$$

Replacing in (11) the numerical values of the parameter and considering the operating time of t_{Pl} =300d·12h/d=3.600 h/a, the *required annual electricity for the pump operation is*:

$$E_{P\text{-}HSP} = P_{P\text{-}PHS} * t_{Pl} = 13,4 *3,6 \triangleq 40\ GWh/a$$

3.2 Estimation the efficiency of PHS

The efficiency of a PHS can be appreciated using the following parameters:

- energy efficiency
- economic efficiency
- amortization period

3.2.1 The energy efficiency

The energy efficiency of the PHS also called productivity index-efficiency is defined as the ratio between the turbine electricity production of $E_{T\text{-}PHS}$ and the consumed electricity of pump $E_{P\text{-}PHS}$:

$$\eta_{PHS} = \frac{E_{T\text{-}PHS}}{E_{P\text{-}PHS}} \qquad (12)$$

This parameter is in fact the overall efficiency coefficient of the PHS and is considered as a relevant productivity index-efficiency indication for the PHS operation [9].

For the considered PHS in our example the energy efficiency is obtained replacing in (12) $E_{T\text{-}PHS}$ and

$E_{P\text{-}PHS}$ from (9) and (11) and considering the operated volume balance $Q_P \cdot t_{tP} = Q_{T\text{-}PHS} \cdot t_{tT}$. The calculated energy efficiency coefficient is:

$$\eta_{PHSPP} = \frac{E_{T\text{-}PHS}}{E_{P\text{-}PHS}} = \eta_T * \eta_P = 0,95 * 0,8 = 0,76 \qquad (13)$$

This value falls into the results of an analysis in the period of 2008-2016 for several European countries which indicate a variation range of the monthly productivity index-efficiency for existing PHS of 0,62 (Austria) to 0,87 (Greece) [9].

3.2.2 Economic efficiency

The economic efficiency of the PHS is defined as the ratio between the incomes from the turbine produced electricity sold at peak load $I_{ncT\text{-}PHS}$ and the electricity costs $O_{CP\text{-}PHS}$ for pump operation at basic load:

$$E_{cef\text{-}PHS} = \frac{I_{ncT\text{-}PHS}}{O_{CP\text{-}PHS}} \qquad (14)$$

Considering the specific cost for the delivered electricity during the turbine operation at peak load e_{spT} (in € / kWh) and the turbine electricity production $E_{T\text{-}PHS}$ formula the incomes $I_{ncT\text{-}PHS}$ from the produced electricity sale at peak load can be expressed as:

$$I_{ncT\text{-}PHS} = e_{spT} * E_{T\text{-}PHS} = \qquad (15) \\ = e_{spT} * \eta_T * \rho * g * Q_{T\text{-}PHS} * \quad_T * t_{Tl}$$

As well the pump operation costs $O_{CP\text{-}PHS}$ can be expressed using the specific cost of the electricity e_{spP} (in € / kWh) and the annual required electricity for pump operation $E_{P\text{-}HSPP}$ (11):

$$O_{CP\text{-}PHS} = e_{spP} * 1/\eta_P * \rho * g * Q_{P\text{-}PHS} * \quad_P * t_{Pl} \qquad (16)$$

Replacing in (15) and (16) in (14) the economic efficiency becomes:

$$E_{cef\text{-}PHS} = \frac{e_{spT}\eta_T\rho g Q_{T\text{-}PHS}h_T t_{Tl}}{e_{spP}\dfrac{1}{\eta_P}g Q_{P\text{-}PHS}h_P t_{Pl}} = \eta_T\eta_P\frac{e_{spT}}{e_{spP}} \qquad (17)$$

For the considered PHS in our example the economy efficiency is obtained replacing in (17) the numerical values for η_T, η_P, e_{spT} and $e_{spT:}$

$$E_{cef\text{-}PHS} = \eta_T\eta_P\frac{e_{spT}}{e_{spP}} = 0,95 \cdot 0,8 \cdot \frac{70}{20} = 2.66 \qquad (18)$$

This value of the economic efficiency parameter is within the characteristic average values for PHS.

3.2.3 Amortization period of PHS

The amortization period is similarly defined as for HPP discussed above in paragraph 2 relation (3) in the case without load and (5) with load considering in this case, additionally to the maintenance operating costs $O_{C\text{-}PHS}$ also the cost of the consumed electricity during the pump operation $E_{C\text{-}PO}$.

a) *The amortization period calculated without load* will be calculated with the following extended form of the formula (3):

$$t_{Am} = \frac{I_{C\text{-}PHS}}{I_{ncT\text{-}PHS} - O_{C\text{-}PHS} - E_{C\text{-}PO}} \qquad (19)$$

$I_{C\text{-}PHS}$ -investment costs of the PHS (€)
$I_{ncT\text{-}PHS}$ -incomes from turbine produced electricity sale at peak load (€/a)
$O_{C\text{-}PHS}$ -maintenance operating costs of PHS (€/a)
$E_{C\text{-}PO}$ -electricity costs for pump operation (€/a)

These parameters should be first determined.
- *Estimation of the investment costs ($I_{C\text{-}PHS}$)*

Noting the specific investment costs *with C_{spT} for turbine, C_{spP} for pump expressed in and C_{sr} for storage reservoir* the investment costs of the PHS can be expressed as:

$$I_{C\text{-}PHS} = C_{spT} * P_{T\text{-}PHS} + C_{spP} * P_{P\text{-}PHSP} + C_{sr} * V_{sr} \qquad (20)$$

where $P_{T\text{-}PHS}$ and $P_{P\text{-}PHSP}$ is the installed power of turbine and pump, respectively. V_{sr} is the storage reservoir volume. Considering the specific investment costs values C_{spT} =1.000 € / kW, C_{spP} =500 € / kW and C_{sr} =20 € / m3 [6], [8], [10] and the above calculated values for $P_{T\text{-}PHS}$, $P_{P\text{-}PHS}$ and V_{sr} the investment cost $I_{C\text{-}PHS}$ for the considered PHS using (12) is: $I_{C\text{-}PHS}$ = 36,7*10^6 €.

- **Estimation the incomes $I_{ncT\text{-}PHS}$**

Noting with e_T the specific cost for the delivered electricity energy E_{TPHS} during the turbine operation at peak load the income through electricity sale is:

$$I_{ncT\text{-}PHS} = e_{spT} * E_{TPHS} \qquad (21)$$

Replacing in this relation the specific cost for the delivered electricity during the turbine operation at peak load of (see given data) of $e_T= 70 \ €/MWh$ and the turbine electricity production of $E_{T\text{-}PHS}= 36 * 10^3 MWh/a$, the income through electricity sale is:

$$I_{ncT\text{-}PHS} = e_{spT} * E_{TPHS} = 70 * 36 * 10^3 = \boldsymbol{2,52 * 10^6 \ €/a}.$$

- **Estimation of pump operation cost $E_{C\text{-}PO}$**

The electricity costs for pump operation can be calculated multiplying the given specific electricity cost at basic load of e_P whit the consumed electricity through pump operation $E_{P\text{-}HSP}$

$$E_{C\text{-}PO} = e_{spP} * E_{P\text{-}PHS} \qquad (22)$$

For the calculation example, the electricity costs for pump operation can be calculated using the given specific electricity cost at basic load of $e_P= 20 \ €/MWh$ (see given data) and the consumed electricity through pump operation of $E_{P\text{-}PHS} \triangleq 40 \ GWh/a = 40 * 10^3 MWh/a$. Replacing these values in (22) on obtain:

$$O_{CP} = e_{spP} * E_{PPHS} = 20 * 40 * 10^3 = 0,8 * 10^6 \ €/a$$

- **Estimation the maintenance operating costs $O_{C\text{-}PHS}$**

Noting whit $e_{BC\text{-}PHS}$ (in $€/kWh/a$) the specific operating costs, the maintenance operating costs $O_{C\text{-}PHS}$ for the PHS is:

$$O_{C\text{-}PHS} = e_{spP} * E_{T\text{-}PHS} \qquad (23)$$

For new constructions, the specific maintenance operating costs of PHS is $e_{BC\text{-}PHS} = 0,7\text{-}1,5 \ ct/ \ kWh/a$ [10]. The considered PHS has an electricity production pro year (calculated above) of $E_{T\text{-}HSP} = 20 \ MW * 1.800h/a \triangleq 36 \ GWh/a = 36 * 10^6 kWh/a$. For an average specific cost of $e_{BC\text{-}PHS} = 1,1 \ ct/ \ kWh/a$ from (23) on obtain the maintenance operating costs of the PHS: $\boldsymbol{O_{C\text{-}PHS} = e_{spP} * E_{T\text{-}PHS} = 0,011 * 36 * 10^6 \triangleq 0,4 * 10^6 \ €}$

Replacing in (19) these numerical values on obtain the amortisation period for the considered PHS extension of the existing HPP: $t_{Am}=28 \ years$

b) The amortization period with load can be calculated with the modified form of (19) replacing the investment cost $I_{C\text{-}PHS}$ with $n \cdot A_{ni} \cdot I_{C\text{-}PHS}$ i.e., considering the cost increase as result of the interest rate when back paying the loan expressed by means annuity factor A_{ni} like in the case of HPP (chapter 2, formulas (5), (6) and (7)). Considering an interest rate of $i = 3\%$ and a term of repayment of $n = 20 \ years$ like as for HPP discussed in chapter 2 we obtain an annuity factor of $A_{n,i}=0,065$ and corresponding to the investment of $I_{C\text{-}PHS} = 36,7 * 10^6 \ €$ on obtain an amortization period of $t_{Am}=36 \ years$. It is to mentions that the obtained amortization periods of $t_A \triangleq 28 \ years$ without loan and $t_A \triangleq 36 \ years$ with loan respectively meet the requirement of an investment for PHS because is less than his technical lifetime of about 35 years [10]

4. CONCLUSIONS

The upgrading of Hydropower (HPP) is a particularly current issue being known that the most of existing HPPs are older than 30-40 years. In this regard in the present paper is presented a simplified calculation example to technical-economic efficiency analysis of upgrading and modernization of a Hydro-power plant (HPP) through re-equipment and extension with a new pump-hydro-energy-storage-unit (PHS). The considered example can be use as orientation basis for the elaboration of preliminary studies to updating of existing waterpower plants. In this regard detailed calculations are presented for efficiency evaluation of modernization and extension of HPP/PHS using parameters such as productivity index-efficiency, economic efficiency, and amortization period (back pay time of investment).

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