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CONCEPTUAL DESIGN OF A PUMPED HYDRO ENERGY STORAGE SYSTEM FOR THE AGUAS CLARAS OPEN PIT MINE

Augusto E. C. Palomino
Felipe Celso Linhares Ferreira
Grupo de Energias Renováveis, Laboratório de Termometria (LabTerm), Programa de Pós Graduação em Engenharia Mecânica PPGMEC, Escola de Engenharia da UFMG
aecaballerop@yahoo.com.br
felipe.linhares.ferreira@gmail.com

Glycon P. S. Barros
Grupo de Energias Renováveis, Laboratório de Termometria (LabTerm), Programa de Pós Graduação em Engenharia Mecânica PPGMEC, Escola de Engenharia da UFMG
glyconb@gmail.com

Luciano Silva
Grupo de Energias Renováveis, Laboratório de Termometria (LabTerm), Programa de Pós Graduação em Engenharia Mecânica PPGMEC, Escola de Engenharia da UFMG
luciano.silva@ifmg.edu.br

Matheus P. Porto
Grupo de Energias Renováveis, Laboratório de Termometria (LabTerm), Programa de Pós Graduação em Engenharia Mecânica PPGMEC, Escola de Engenharia da UFMG
matheusporto@demec.ufmg.br

Summary. *The power supply from renewable sources such as photovoltaic and wind occurs in several aspects, and energy storage combined with the weather forecasting is seen as the solution to mitigate this variability. For this, we propose an alternative of pumped hydro energy storage, an open pit mine called Águas Claras, located in Belo Horizonte, which has large hydraulic energy storage potential. Photovoltaic panels will be used as a main energy source for power supply, during off-peak periods of demand or during periods of low variability, the pumps will operate to provide the storage, while during a peak demand of energy, water will be consumed by a hydraulic turbine to recover energy.*

Keywords: *Pumped Hydro Energy Storage, Energy Storage, Águas Claras Open Pit Mine*

1. INTRODUCTION

One of the obstacles in the use of photovoltaic and wind energy is the inherent variability, which could be reduced with energy storage (Notton, et all., 2011).We provide here a case study in which a photovoltaic plant is combined with pumped hydro energy storage (PHES) during off-peak energy demands(Kušnír, et all., 2010) to provide a great source of energy storage.

Developed countries are working on energy storage technologies to improve the use of natural resources (Shabrina, et all., 2014), and in recent years has greatly increased commercial interest in PHES (Deane, et all. 2010).

There are several energy storage technologies being used nowadays, including Lithium batteries, CAES (Compressed Air Energy Storage), PHES (pumped hydro energy storage) and CES (Cryogenic Energy Storage). The PHES and CAES/CES are currently most promising energy technologies on large scale, and PHES is the most used in the world (Yang and Jackson, 2010).

According (Anagnostopoulos and Papantonis, 2008), PHES is used to store energy from off-peak demand, pumping water from a lower reservoir to a higher one. In a higher demand of energy, water from the upper reservoir goes down by a penstock and passes through a turbine (usually the Francis type), thus providing the energy needed to supply the peak demand of energy. The water can be pumped using the turbine itself (Hydro News, 2012) or by hydraulic pumps, which in this case can be driven by photovoltaic or wind power, thus storing potential hydraulically energy.

(Gesc, 2014) proposes the construction of a reversible mill besides of a solar farm of 100 MW (Sacaton, Arizona), using for this the disabled open pit mine as the lower reservoir, requiring the construction of an upper reservoir. These energy storage systems have many applications as hold a charge, stabilize voltage and frequency, manage power surges, improve power quality and postpone upgrade investments in generating (Notton, et all., 2011).

(Phillips, 2013) analyzed the potential of New South Wales (Australia) for the use of sea water in the PHES, as shown in Figure 3. In this case the sea is the lower reservoir.

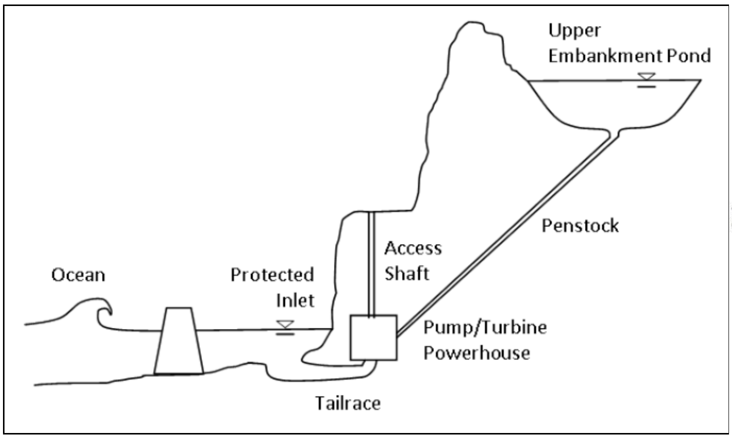


Figura 3. *Potential of Pumped Storage in New South Wales*
Source: *MS Phillips, WL Peirson and RJ Cox ,* 2013

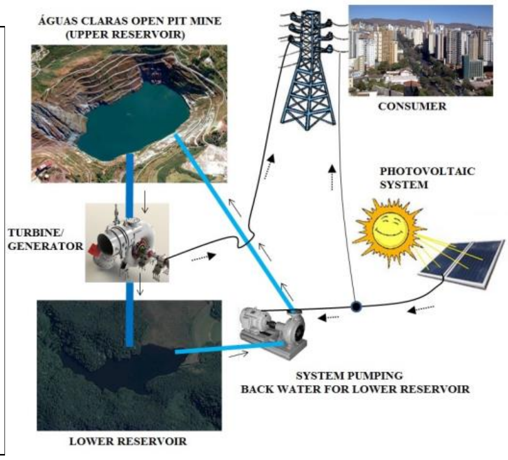


Figure 4. Use of Aguas Claras mine as reversible hydroelectric plant as an integrated energy storage with photovoltaic system.
Source: Authors

Figure 4 illustrates the layout and operation of reversible hydropower plant proposed in this paper, using open pit mine Aguas Claras in Minas Gerais, as upper reservoir to store hydraulic energy potential and using in an integrated way the photovoltaic solar energy to supply the system pumping. This proposal is similar in structure, size and gap between the lakes of Olivenhain-Hodges plant (Kaneshiro, et all., 2006).

The basic idea is to generate electricity during two to three hours at rush times. This generation period can be used to enhance the system's needs. During the day there is the water stored in the main tank, this reserve can be fueled at any time of the day, the energy generated can also be used as an emergency (no-break). This service will be partial owing to the turbine's limited capacity.

2. CHARACTERISTICS OF AGUAS CLARAS OPEN PIT MINE

The Aguas Claras open pit mine is located next to Mangabeiras Park (Belo Horizonte / MG, Brasil), as illustrated in Figure 5. According to (Grandchamp and Velásquez, 2002), Aguas Claras was responsible for the MBR growth towards the international iron ore market. For many years, it was the main operating unit of the company, with a production capacity of 12 million tons per year.

Figure 5. View of Lake formed in Aguas Claras Mine and its location
Source: Google Maps (adapted), accessed on 14.06.2015.

According to (Grandchamp and Velásquez, 2002) the main morphometric characteristics of Aguas Claras Lake are: 67 hectares, moorhen mirror quota 1100 meters, volume of 58 million cubic meters, 234 m of maximum depth, 3772 m perimeter, an average depth of 87 meters and relative depth of 25%. According to him, the following items a, b, c and d, were calculated, after performing water balance considering precipitation, direct rainfall on the lake, runoff, external supply, groundwater inflow, the lake blade evaporation, direct recharge, recharge side.

a. The groundwater supply has small variations around 200,0 m³/h;

b. The lateral recharge is evidenced in the days when there is a large supply of water to the lake due to the rain system that causes a quickly rise in the cava water level;

c. Although the lake system works as an aquifer recharge his balance point is always positive, it means that the water accumulation is greater than the lateral infiltration;

d. In the months in which there is hydrological deficit, it means, higher evaporation than rain precipitation, the pit filling is ensured by underground supply.

From the analysis of these characteristics, it is possible to look foward to the implementation of PHES in Aguas Claras open pit mine, thus generating the necessary support to the energy demand of Belo Horizonte city.

3. HIDRAULIC SIZING

The first step to verify the conceptual design is to check the maximum power and determine the power generated on booster pump. The Figure 6 shows a sketch of the plant.

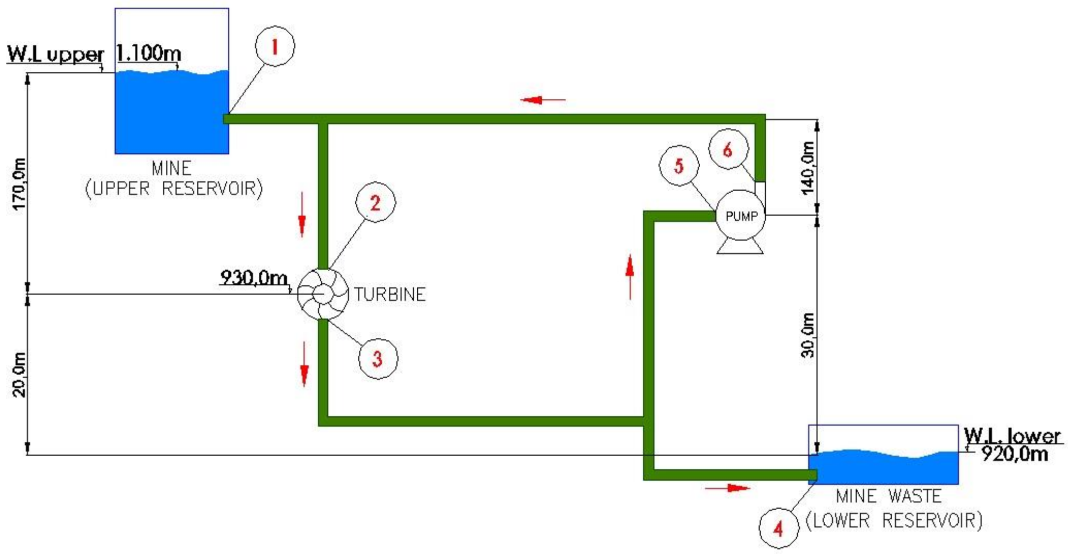


Figure 6. Flowchart of the proposed system
Source: Authors

Nomenclature

Q water flow, m³/s	P pressure, mca	**Subscript**
V speed of water runoff, m/s	$P_{disp.,trecho}$ available pressure in the indicated section, mca	*mt* maximum turbine
A area of the section which takes water runoff, m²	C roughness of the conduit walls / pipe (dimensionless)	*av.* available
ΔH pressure loss indicated stretch, mca	K pressure loss coefficient (dimensionless)	*am.* amount
D diameter, m		*jus.* jusant
L_{eq} length of the indicated stretch (m)	**Greek symbols**	*h* hydraulic
g gravitational acceleration, m/s²	Σ sum	
H_G geometric gap, m	η efficiency	
UR upper reservoir		
LR lower reservoir		

The flow rate is defined by Eq. (1) according to the maximum rate flow in the pipes ranging from 1.5 to 4.5 m/s, this speed being considered economic (Netto and MArtiniano, 2000).

$$Q = VA \tag{1}$$

For the turbine circuit, was adopted the speed flow of 2.5 m/s and diameter penstock of 1.0 m. For the pump circle, was adopted the speed flow of 1.5 m/s and maximum diameter of 1.0m of water return pipe. Then:

$Q_{mt} = 1{,}96\ m^3/s$ e $Q_{mp} = 0{,}5\ m^3/s$

To calculate the pressure loss in the straight section of the penstock and discharge piping, the equation of Hazen-Williams will be used, which is used for straight stretches. The results are shown in Tab. 1 and 2.

$$\Delta H_{stretch} = 10{,}643.Q^{1,85}.C^{-1,85}.D^{-4,857}.L_{eq} \tag{2}$$

Table 1. *Pressure loss* in straight sections of the turbine and pump circuit

	Stretch	Q	C	D	Leq	ΔH
Turbine	1 - 2	1,96	100$^{(1)}$	1,00	2.000,00	15,37
	3 - 4	1,96	100$^{(1)}$	1,00	300,00	2,89
	ΣΔH =					18,26
Pump	4 – 5	0,50	100$^{(1)}$	1,00	20,00	0,32
	6 - 1	0,50	100$^{(1)}$	1,00	2.000,00	1,44
	ΣΔH =					1,76

(1) Roughness surface for molten iron pipes with use of 20 years.

To calculate the pressure loss cocated (in plumbing accessories) in the penstock excerpt and discharge piping, the Eq. (3) will be applied. The results are shown in Tab. 2.

$$\Delta H_{tstretch,accessories} = K\frac{V^2}{2g} \tag{3}$$

Table 2. Pressure loss in the turbine accessories circuit and pump

	Stretch	Q	Accessories	Quantity	K	K_{total}	ΔH
Turbine	1 - 2	1,96	Normal entrance	1	0,5	0,5	0,16
			Tee (line to branch flow)	1	1,3	1,3	0,41
	$\Sigma\Delta H_{1-2}$ =						0,57
	3 - 4	1,96	Curve 90°	2	0,4	0,8	0,25
			Tee (line to branch flow)	1	1,3	1,3	0,41
	$\Sigma\Delta H_{3-4}$ =						0,66
Pump	Stretch	Q (m³/s)	Accessories	Quantity	K	K_{total}	ΔH (mca)
	4 - 5	0,5	Normal entrance	1	0,5	0,5	0,06
			Curve 90°	2	0,4	0,8	0,09
			Tee (line to branch flow)	1	1,3	1,3	0,15
	$\Sigma\Delta H_{4-5}$ =						0,30
	6 - 1	0,5	Retention valve	1	2,5	2,5	0,29
			Butterfly valve	1	0,3	0,3	0,03
			Curve 90°	1	0,4	0,4	0,05
			Tee (line to branch flow)	1	1,3	1,3	0,15
			Normal entrance	1	0,5	0,5	0,06
	$\Sigma\Delta H_{6-1}$ =						0,58

The pressure available in this study is calculated below in Eq. (4). This pressure will be calculated for the available circuit amount of the turbine and jusant of the booster pump.

$$P_{av.,stretch=} \pm H_G - \Delta H_{stretch} \tag{4}$$

Where *Hg* is the geometric gap of water point to the circuit input.

Tab. 1 and 2 shown the results of total pressure loss. It is possible to calculate the hydraulic power of the turbine and pump using Eq. (5) and Eq. (6) respectively.

$$N_{h,turbine} = \rho.g.P_{av.,am.,turbine}.Q_{max.,turbine} \therefore N_{h,turbine} = 2{,}98MW \tag{5}$$

$$N_{h,pump} = \rho.g.\left(P_{av.,am.,pump} + P_{av.,jus.,pump}\right).Q_{max.,pump} \therefore N_{h,pump} = 0{,}79MW \tag{6}$$

The electrical power of the turbine and the pump is calculated by multiplying the hydraulic power values obtained from Eq. (5) and Eq. (6) with the yield of each product. It adopted commercial yields, included 85.0% for the turbine, 98.0% for the generator, 78.0% for the pump and 98.0% for the pump drive engine. Thus, obtaining the following electric-power values:

$$N_{electrical,turbine} = \eta_{turbine}.\eta_{generator}.N_{h.,turbine} \therefore N_{electrical,turbine} = 2{,}48MW \tag{7}$$

$$N_{electrical,pump} = \frac{N_{h.,pump}}{\eta_{pump}.\eta_{motor}.} \therefore N_{electric,pump} = 1{,}06MW \tag{8}$$

The generating efficiency is calculated using the generation circuit yields according to Eq. (9) below:

$$\eta_{generation} = \eta_{turbine}.\eta_{generation}.\eta_{pump}.\eta_{motor,pump} \therefore \eta_{generation} = 62{,}38\% \tag{9}$$

4. USE OF PHOTOVOLTAIC SOLAR ENERGY TO PUMP TO UPPER RESERVOIR

The energy produced by the solar plant should be able to feed a pumping system for the Reversible hydroelectric plant (PHES) whose estimated power is 1.06 MW.

The exposure period of theoretical sun, considered to generate electricity through the solar plant will be from 09 to 15 hours, totaling 6 hours of daily generation during 365 days/year. Throughout the year, this time is variable due to weather conditions such as cloudy, rainy season and seasons in which the electricity generation is decreased.

For this project, it is considered conservatively the period generate between 10 and 15 hours. Any time of more generation will be launched on the network as "savings" to be used when needed.

The operation of PHES is limited to the storage capacity of the lower reservoir. The maximum continuous period of PHES generation will be 16 hours, during this time the lower reservoir would be completely full. The PHES is planned to operate and suply demand at rush times from 7pm to 10pm, totaling 3 hours daily. If the operation of the PHES outside these hours is required, this condition shall be verified of the available capacity of the lower reservoir and the regulation of the Operador Nacional do Sistema Elétrico (ONS) 1[1].

Once the water volume available in the lower reservoir, it will be necessary to pump it towards the upper reservoir. For the generation of 3 hours PHES, is required 6 hours for pumping. If the generation PHES is greater than three hours, Will be necessary to calculate a new pumping time.

In the Engineering Manual for Photovoltaic Systems, item 5.5.1, (Anagnostopoulos and Papantonis, 2008), are clarified the two possible systems isolated or connected installation in the distribution network, due to 1,06MW pumping capacity, the plant will be considered within the system power compensation.

In this paper we consider the interconnected system option in the distribution network, with electricity availability for pumping if necessary.

For the design of the power generated by photovoltaic panels we used the criterion of "Solar Peak Time", which corresponds to the number of hours per day to 1.000,00W / m². For example, 5 hours of sun peaks + 5 kWh/m² is the energy received for a total number of hours a day equivalent to the energy received by insolation 1,000.00 W / m² during 5 hours. (Lopez, 2012)

The solar panels were chosen in the Solar Yingle manufacturer market, (Yingli Green Energy Holding, 2012) Model: YGE 60 cells of 40 mm - Serie YL24P-29b. It was selected this model by dimensions that provide easy handling and transportation to the installation location.

The solar plants installation requires a solar cell panels on a very large area, it must be taken into account the correct distance of the panels rows one behind the other to prevent the panels from shading on each other, as that this condition is very harmful to the performance of photovoltaic systems, it means, maximize the area of load factor (Villalva and Gazoli, 2012). Due to the irregular area of Aguas Claras mine, in the project was considered that the area required for installation of the solar plant will be 4 times the total area of the panels.

Table 3 reports the summary of the calculations of photovoltaic system required in this project.

[1] The ONS is the entity that has the following duties to coordinate and control the operation of facilities for generation and transmission of electricity in the National Interconnected System (SIN).

Table 3. Scaling with commercial photovoltaic
Source: Authors

IMPUT DATA		
Description	Value	Unit
Daily average of solar irradiation for BH	4,33	kWh/m²day
Exposure Day	1,0	Day
Irradiation hours	6,0	Hours
Irradiation received	722,00	W/m²

DATASHEET PANEL: **YGE 60 CELULAS DE 40mm - SERIE YL245P-29b - Yingle Solar**		
Description	Value	Unit
Efficiency	15,0	%
Energy produced by the module	245,0	W
Area	1,63	m²

RESULTS		
Description	Value	Unit
Number of panels needed (added in 3%)	4.456,0	Parts
Wp installed	1,06	MWp
Total area occupied by modules	7.279,0	m²
Service area (hallways, room to maneuver, etc.)	21.838,0	-
Office areas and panels room	100	m²
Total area required	29.218,00	m²

5. MANAGEMENT OF THE ELECTRICITY GENERATED SYSTEM

The energy management planning generated with photovoltaic panels will be made daily. The assumptions for electricity generation and daily operation of reversible hydropower plant proposed in this paper are:

a. a. Availability of skilled operators;

b. The capability of the lower reservoir (LR) limits the daily electric power generation (EE) by the period of 16 continued operation hours;

c. Installing a solar plant with photovoltaic panels, generating the equivalent of maximum 12 hours a day, we would have this power being discharged strategically on the network as a "savings" when necessary to pump the water back into the lower reservoir (LR) for the upper (UR) at any time of day or night. The production of electricity in the PHES can be considered as “nobreak” and used as a strategic reserve in case of a lack of full electricity (blackout). Must be installed adequate safeguards for the entire electrical system.

d. It is possible with the electricity generated by the solar plant to pump from the lower reservoir water (LR) to the upper reservoir (UR) in appropriate time, as it may be limited to atmospheric conditions of cloudy day or rain. In this project the plant will be connected to the network;

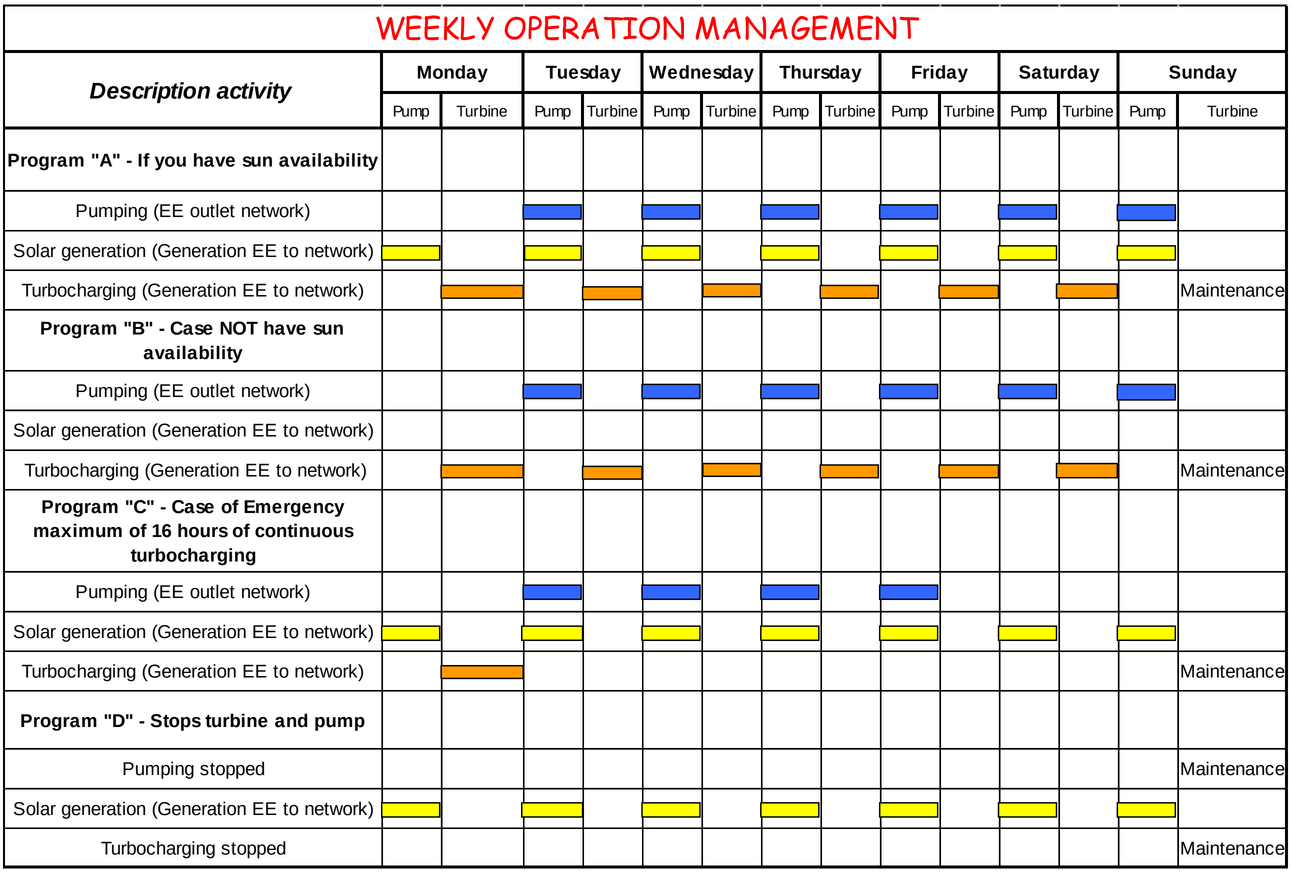
e. In order to have power constantly at any time, the best condition is to use the "savings", in the distribution network. The production of electricity in the PHES can be programmed for 3 or 4 peak hours, depending on the regulation of ONS;

f. Because of the frequent starts and stops, it is necessary to deploy a "Maintenance System based on Reliability, Maintainability and Availability proactively" being applied in hydroelectric and solar power plants, as discussed (Lafraia , 2011).

To maximize the generation and system economy, will be studied and developed alternative programs for energy management planning generated with the PHES and photovoltaic panels. In these studies, it will be taken into consideration the best time to return water pumping from the lower reservoir to the upper.

Figure 7 presents the Weekly proposed operation management of the PHES.

Figure 7. Proposed operation management of the PHES
Source: Authors



6. RESULTS

With the Reversible hydroelectric plant (PHES) implementation at Aguas Claras, it will be possible to produce up to 2,48MW of electric power, at the high demand time, however the consumption of the water pump process to the upper reservoir will be of 1,06 MW. These pumps consumptions will be supplied by the electrical power from the photovoltaic system with 4,456 panels installed in the area working during the day, so the power consumed by the pumps will not be deducted from the power generated by the photovoltaic system, resulting in 2,48MW to be used directly by Belo Horizonte city electricity demand.

Table 04 summarizes the results.

Table 4. Overall results
Source: Authors

Description	Value	Unit
PHES power capacity	2,48	MW
Electric power pumps demand	1,06	MW
Daily average of solar irradiation for BH	4,33	kWh/m²day
Number of panels needed (added in 3%)	4.456,0	Parts
Generating efficiency	62,38	%

7. CONCLUSION

The energy generated will be available on the main transmission line. Therewith, some power plant connected to the system can have its production of energy reduced corresponding to the amount provided by the proposed plant, representing savings in the use of water in the reservoir.

In this project, we have water available at the mine cava and the lower reservoir available to close the hydraulic system, thus making the reuse of available water. The efficiency of generation of 62.38% is very close to what is expected in ideal conditions for reversible power plant (64%).

It is recommended that the plant be located near the main transmission network to facilitate interconnection to avoid large transmission losses. The region chosen has this condition, since the location is in the urban region of Belo Horizonte, that is behind the mountain wall in the neighborhood of Mangabeiras.

8. REFERENCES

Anagnostopoulos, J. S.; Papantonis, D. E. Simulation and size optimization of a pumped storage power plant for the recovery of wind farms rejected energy. Renewable Energy, v.33, p.1685-1694, 2008.

Andritz Hydro. Revista Hydro News. Número 21. 2012. p 5.

CEPEL-CRESESB. Manual de Engenharia para Sistemas Fotovoltaicos. Organizadores: João Tavares Pinho, Marco Antônio Galdino. Grupo de Trabalho de Energia Solar, 2014. Rio de Janeiro. p 290.

Deane, J.P. and Gallachóir, B.P. and McKeogh, E.J., 2010. Techno-economic review of existing an new pumped hydro energy storage plant. Renew Sust Energy, v.14, p. 1293-1302.

Grandchamp C. A. Paulino, Velásquez L. N. Menegasse . Determinação Do Balanço Hídrico Na Recuperação Do Nível De Água Do Aquífero Cauê Na Mina De Águas Claras, Serra Do Curral, Município De Nova Lima, Minas Gerais. , 2002. XII Congresso Brasileiro de Águas Subterrâneas. São Paulo.

Green Energy Storage Corp. Preliminary Permit - Sacaton Pumped Storage Project., 2014. Peoria, AZ.

Kaneshiro, J. and Piek, L. and Lee, K. and Korbin, G. and Carlson, J. and Ramsey, M., 2006. Emergency Storage Project: design and construction of the Lake Hodges to Olivenhain tunnel pipeline. Tunn Undergr Space Technol, San Diego, California. v.21, p.340.

Kema Inc. Market Evaluation for Energy Storage in the United States, , 2012. Virginia, USA.

Kušnír, S. and Krištof, V. and Marci, M. and Katin, M. and Csányi, L., May 2010. Pumped Storage Hydro Power Plants in Slovak Republic. Intensive Programme “Renewable Energy Sources”,UWB, CZ, p.35-38.

Lafraia J. R. Barusso. Manual de Confiabilidade, Mantenabilidade e Disponibilidade., 2011. Qualitymark. Rio de Janeiro.

MS Phillips, WL Peirson and RJ Cox., 2013. A Brief Appraisal of the Potential of Pumped Storage in New South Wales. Water Research Laboratory, Australia.

Netto, Azevedo, Martiniano, José, 2000. Manual de Hidráulica. 8ªEdição. Editora Edgard Blucher Ltda, São Paulo. p 223.

Notton, G. and Lazarov, V. and Stoyanov, L., 2011. Analysis of Pumped Hydroelectric Storage for a Wind/PV System for Grid Integration. Екологично инженерство и опазване на околната среда, No 1, p. 64-74.

Ricardo A. Lopez., 2012. Energia Solar Para Produção de Eletricidade. Editora Artliber. p 39.

Shabrina, N. and Wakao, S. and Nagura, O., 2014. Operation Design of a Pumped Storage System in a Residential Area with Mass PV Introduction. AORC Technical Meeting 2014.

Villalva M. G., Gazoli J., 2012. Energia Solar Fotovoltaica. Conceito e Aplicações. Sistemas Isolados e Conectados à Rede. Editora Erica Ltda. p 64.

Yang, C.-J. and Jackson, R. B., 2010. Opportunities and Barries to Pumped-Hydro Energy Storage in the United States. Renewable and Sustainable Energy Reviews, v.15, p.839-844.

Yingli Green Energy Holding Co., 2012. Catálogo Técnico YGE 60 CELL 40 mm Series 2012.