Gravity Compressed -Air- Hydraulic- Power-Tower Energy Storage Plants

Ioan David, Camelia Stefănescu
Politechnica University of Timisoara, Department of Hydrotechnics, Str. George Enescu I/A, 300022 Timisoara, Romania
Ioan.david@gmx.net

Abstract. In the era of the increasing implementation of renewable energy sources in the electrical energy supply the demand for energy storage continues to grow. This is because the renewable energy sources, mainly in the form of wind and solar energy, are sustainable, but at the same time are subject to natural fluctuations. The wind does not always blow, and the sun does not always shine. Therefore, a stable and reliable power supply is more challenging than ever. It now must regulate fluctuating electricity demand and fluctuating electricity supply. At the same time decentralized energy supply systems based mainly also on PV and wind energy (e.g. as hybrid systems) storage requirement will become a key component of these local electrical energy supply networks especially to balance the energy demand and supply. Among the many storage techniques an important example is the Hydro-Power-Tower an innovative hydraulic energy storage system based on pumped storage technology. Depending on the actual storage method that can be based on gravity (lifting / falling of weight in a vertical underground or above ground Tower), on air compression / decompression or on a combination of both techniques, can be distinguished the following Storage systems, Gravity Hydro Power Tower Storage (GHPTS), Compressed Air Hydro Power Tower Storage (CAHPTS) and Gravity Compressed Air Hydro Power Tower Storage (GCAHPTS). The GHPTS is the classic form of the Hydro Power Tower Storage and is widely discussed in the literature with scientific results and technical applications especially in the last decade. Besides the many advantages of (GHPTS) an important disadvantage is the very high weight and high cost of the tower piston (usually metal) which is the key component for potential energy storage. The storage based on Compressed Air is also widely applied in different storage systems but less so than Power Tower. Regarding the application of compressed air, in the PTS system, some own results are to mention, proposing a replacement possibility of the heavy overload piston of (GHPTES) using a part of the tower as a compressed air reservoir. The present study considers the combination of both storage techniques Gravity and Compressed Air integrated in a so-called Gravity-Compressed-Air-Hydro- Power- Tower - Storage (GCAHPTS). The combined influence of compressed air pressure and high of weight tower piston on the stored energy will be analysed. The obtained results allow the optimal design of such a combined power tower storage system. When the compressed air or high weight piston is missing on obtain GHPTS or CAPTS respectively.

1. Introduction
Energy storage systems (ESS) generally serve to balance energy generation and demand. At the same time, they can compensate for unregulated, fluctuating energy supplies such as photovoltaic and wind energy, improve supply security and stabilize the power grid. Another aspect of the increasing use of renewable energy in electricity supply is, that in contrast to the formerly central energy supply with
fossil fuels, the renewable energies such as photovoltaic and wind power plants are mainly decentralized to the natural boundary conditions, even in areas with weakly developed network infrastructure. This leads to similar problems which can be solved only using adequate electrical energy storage.

Consequently, electricity storage plays a key role in the proper functioning of electricity supply systems which importance and indispensability increase with the increasing share of renewable energy in the energy mix, a current and perspective objective of the global energy policy.

A comprehensive overview and analysis of the current development of various types of energy storage technologies, from the recent achievements of the state-of-the-art in Electrical Energy Storage (EES) is presented in [1].

It is shown that the EES, whose share in energy supply is steadily increasing, can have multiple functions to power network operation and load balancing, such as: helping in meeting peak electrical load demands, alleviating the intermittence of renewable source power generation, improving power quality/reliability, supporting the realization of smart grids, helping with the management of distributed/standby power generation, reducing electrical energy import during peak demand periods. Under the EES the standard Pumped Hydropower Storage (PHE) deployed worldwide, mainly due to its technological maturity. They are the most efficient large-scale electricity storage systems yet, but due to their function they are in mountain regions having also severe siting limitations due to the need for two large reservoirs at different elevations and the resulting environmental disruption [1-5].

The use of compressed air is another important energy storage possibility which is also widely treated in the technical literature [7].

In difference to this works a relatively new and innovative energy storage system based on pumped storage technology is the Gravity Hydro Power Tower Energy Storage system (GHPTES). Both GHPTES as small EES system of some kWh and as EES system of higher capacity of MWh have been developed mainly in the USA and Germany [3-6]. It consists of a vertical cylindrical tower (i.e. vertical shafts as the main bore called storage tower), filled with water, in which moves a heavy overload piston e.g. from steel at smaller storage systems or from the native rock at very large storage systems which use mine shaft as power tower. Besides the many advantages of (GHPTES) an important disadvantage is the huge weight of the overload piston made of expensive heavy material (e.g. steel) which can leads to restriction of application the power towers energy storage at photovoltaic or wind power plants which are mainly decentralized to the natural boundary conditions. A replacement possibility of the electrical energy storage with gravity technic using of huge and expensive heavy overload piston of (GHPTES) offers the use of compressed air. So, we obtain a new power tower storage which can be named Compressed Air Hydro Power Tower Energy Storage (CAHPTES). Such a storage power tower was analyzed in [8]. A comparative operating scheme as well as comparative calculations method, among others for energy storage for the two systems are presented. It was shown that the proposed compressed air-based energy storage system (CAHPTES), even at an ordinary air pressure of some bar (e.g. 3-7 bar) can eliminate several tones of heave overload weight material (e.g. 30-700 tone steel) maintaining the same energy storage as the (GHPTES).

In the present study a combination of both storage techniques Gravity and Compressed Air integrated into Gravity-Compressed-Air-Hydro- Power- Tower - Storage (GCAHPTS) will be presented. It will be analyzed the combined influence of both compressed air pressure and weight overload piston on the power tower stored energy. The obtained results allow the comparative analysis and optimally design of such a combined power tower storage system. When the compressed air or the heavy overload piston is missing on obtain CAHPTS or GHPTS respectively.
2. Comparative overview of GHPT- and CAHPT Energy Storage systems

Provide the Gravity Hydro Power Tower Energy Storage system (GHPT-ES) have been discussed in [3-6]. In connection with the GHPT-ES it should be mentioned that in addition to the numerous advantages of this energy storage system, the heavy overload piston (usually made of iron) is a rather big disadvantage, both from technical difficulties when transporting this object to the execution site of the system and also from increased costs.

Possibility to replacement of the gravity-based energy storage using heavy overload weight piston through compressed air-based storage (i.e. CAHPT-ES) was analyzed in [8]. Figure 1 shows the basic scheme of both GHPT- and CAHPT-ES systems.

![Figure 1. Schemes of the GHPT-ES (a) and CAHPT-ES (b-initial phase, c-end storage phase)](image)

H_T - is the height of storage power tower; H_G - is the height of weight overload piston
H_W - is the height of water in the tower; H_{a1} - is the height of the air reservoir at initial pressure

The energy storage/production of the classical GHPT (figure 1 a) noted E_{GHPT} is expressed as follow:

$$E_{GHPT} = \rho_W g \left( \frac{\rho_G}{\rho_W} - 1 \right) A_T H_T^2 F(\lambda_G)$$

where :

$$F(\lambda_G) = \lambda_G(1 - \lambda_G) = \lambda_G \lambda_W; \quad \lambda_G = \frac{H_G}{H_T}; \quad \lambda_W = \frac{H_W}{H_T};$$

Notations: \(\rho_G\) is the specific mass of the used material for the overload piston; \(\rho_W\) is the specific mass of water; \(A_T\) is the cross-section area of the power tower; \(g\) is the gravity acceleration.

The term "classic" refers to the fact that the water during energy production through the fall of the heavy piston is directed into the space above the pistons (therefor the factor \((\rho_G/\rho_W-1)\).

The relation (1) shown that the energy storage/production \((E_{GHPTS})\) of the GHPT depends on the ratio between the height \(H_G\) of the overload heavy pistons and the height \(H_T\) of the power tower, expressed through parameter \(\lambda_G\) over the function \(F(\lambda_G)\). The maximum energy storage-production according to \(F(\lambda_G)_{\text{max}}\) on obtaining for \(dF(\lambda_G)/d\lambda_G=0\) resulting \(\lambda_G=0.5\).
The CAHPT (Figure 1 b, c) which replace the GHPT (Figure 1 a) having the same storage capacity proposed in [8], has two parts a first part with the height $H_W$ as water tank with free level situated in the lower part of the power tower and a second part for compressed air situated in the upper part of the power tower having a height of $H_a = H_T - H_W$.

Figure 1 b depicted the initial operating phase of CAHPT when the pressure in air tank has a value of $p_{a2}$. This pressure is generated by a air compressor which put into operation only one time namely at the first operating phase of the hydro-power-tower.

During the storage operating phase (figure 1) the pump/turbine unit (P/T) pumps water into upper part of tower compressing the air until the maximum pressure $p_{a2}$ is reached (i.e. the pressure that is admitted from the resistance of the walls of the tower air tank).

During electricity generation, the high-pressure air ($p_{a2}$) push back the water into the lower part of the tower, driving the hydro turbine to generate electrical energy. By setting the volume ratio of air and water reasonably, the largest amount of energy can be stored, maximizing the utilization of storage devices. The air compressing and dilatation during the energy storage/generation is assumed as isothermal process. Consequently, the relationship between the volume and pressure is those of an ideal gas can be expressed as

$$p_{a1}(1-\lambda_w) = p_{a2}(1-2\lambda_w)$$

where

$$\lambda_w = \frac{H_W}{H_T}; \quad \lambda_z = \frac{z}{H_T}$$

For a given $p_{a2}$ (i.e. the pressure at the end of storage cycle) the required initial pressure $p_{a1}$ in the air tank can be determine using relation (1). The stored energy of the CAHPT for a given $H_T$ and given pressure $p_{a2}$ which is the maximum accepted pressure that is admitted from the resistance of the air tank walls) can be expressed as follow:

$$E_{CAHPT} = p_{a2} A_T H_T F(\lambda_w)$$

where

$$F(\lambda_w) = (1-2\lambda_w)ln\frac{1-\lambda_w}{1-2\lambda_w}$$

It should be pointed and underlined that the classical GHPT and the proposed CAHPT have the same tower height $H_T$ (figure 1). This note is important because it can be considered another variant of CAHPT namely when the lower water container is not integrated in the tower but is placed outside separate from tower. This case will be discussed in another paper. The previous own paper [8] and the present paper assume that the water container is integrate in the tower (figure 1).

In Table 1 an extract from results obtained in [8] regarding the comparison storage capacity of both GHPT and CAHPT is presented. The comparative results shown that compressed air-based energy storage system (CAHPT) for pressures of some bar (e.g. 3-7 bar) can replace the storage capacity of several tones of heave overload weight material (e.g. 30-700 tone steel) maintaining the same energy storage as the (GHPT) at the same height of the tower. For example, a medium capacity gravity hydro tower (GHPT) with a tower height of $H_T$=10m and diameters of 1-5 m having a weight overload piston of 30-766 tons steel can store in one operating cycle about 0.4-37 kWh energy. The same energy can be stored with a compressed air hydro power tower (CAHPT) at a maximum pressure of 7,3 bar.
Table 1. Performance comparison of GHPT and CAHPT for some usual characteristic parameters

| DT [m] | 5     | 10   | 20   | 50   |
|--------|-------|------|------|------|
| G      | E_GHPT | p_a2 | p_a1 | E_CAHPT |
| [t]    | [kWh] | [bar]| [bar]| [kWh]  |
| 1      | 15    | 0.09 | 3.6  | 7.3   | 14.6  |
| 2      | 61    | 0.37 | 122  | 244   | 5.9   | 60.0 |
| 3      | 138   | 0.83 | 276  | 552   | 13.3  | 1.380 |
| 5      | 383   | 2.30 | 766  | 1.532 | 36.9  | 3.830 |
| 10     | 1.530 | 9.20 | 3.060| 6.120 | 147.6 | 15.300 |

Notes on table content
- Columns $E_{GHPT}$=$E_{CAHPT}$ represents the stored energy in both compared systems GHPT and CAHPT respectively in kWh, corresponding to different tower diameter $D_T$.
- Columns $(p_{a2}; p_{a1})$ represent the values of maximum and initial air pressures in the air tank of CAHPTS.

In the next paragraph a combination of both gravity-based storage and compressed air-based storage in a power tower called Gravity-Compressed Air-Hydro-Power-Tower noted GCAHPT will be discussed.

3. Combined Gravity Compressed-Air Hydro Power Tower Energy Storage

In Figure 2 are depicted the principle scheme of all three power tower systems: the gravity-hydraulic power tower (GHPT) and the compressed air hydro power tower (CAHPT) discussed above as well their combination named gravity compressed air hydro power tower (GCAHPT) which will be presented in the following. It is assumed that the water container is integrate in the tower and both towers have the same height $H_T$.

![Figure 2. Principle schemes of the CAHPT and the GCAHPT energy storage systems](image)

The CAHPT (left in figure 2) discussed in [8] use only the compressed air-based energy storage through the air pressure change in the upper part of the tower ($p_{a1}$ to $p_{a2}$) through the air volume change
from $V_{a1}=A_T H_{a1}$ corresponding to the initial operation phase to $V_{a2}=A_T H_{a2}$ corresponding to the end phase of the storage operation cycle.

The proposed Gravity-Compressed-Air-Hydro-Power-Tower (GCAHPT figure 2 right) presented furthermore integrates both storage techniques gravity and compressed air respectively. The tower has the same height $H_T$ and integrates the water reservoir in its lower part having a height of $H_W$. The upper part having a height of $H_{a2}$ contains the heavy overload piston of height $H_G$ and the compressed air part having a height of $H_{a2}$. In the initial operating phase, the air occupies a part of the tower have a height of $H_{a1}=H_{T} - H_G$ and has a pressure of $p_{a1}$. During the energy storage operation, the water is pumped from the lower reservoir into the upper part of the tower. The energy storage arises through air compressing above of the heavy overload piston and through lifting the heavy overload piston. The compressed air-based energy storage arises through the air pressure change from $p_{a1}$ to $p_{a2}$ following of the air volume change from $V_{a1}=A_T (H_{a2}+H_W)$ to $V_{a2}=A_T H_{a2}$. At the end of the storage operation cycle the air pressure reached the maximum value of $p_{a2}$ "figure 2" right. The maximum pressure $p_{a2}$ is limited by resistance of the air tank wall. The gravity-based storage is achieved at the same time through lifting the heavy overload piston with the height of $H_W$.

The entire stored energy of the GCAHPT during an operating cycle is obtained summing both gravity-$E_{GHPT}$ and compressed-air-based storage $E_{CAHPT}$:

$$E_{GCAHPT} = E_{GHPT} + E_{CAHPT}$$

where

$$E_{CAHPT} = p_{a2} A_T H_T F_{CA}(\lambda_W, \lambda_G)$$

$$E_{GHPT} = \rho_G g A_T H_T^2 F_G(\lambda_W, \lambda_G)$$

in dimensionless form:

$$e_{CA} = \frac{E_{CAHPT}}{\rho_w g A_T H_T^2} = \alpha_{a2} F_{CA}(\lambda_W, \lambda_G)$$

$$e_{G} = \frac{E_{GHPT}}{\rho_w g A_T H_T^2} = \alpha_{G} F_G(\lambda_W, \lambda_G)$$

$$e_{GCA} = \frac{E_{GCAHPT}}{\rho_w g A_T H_T^2} = \alpha_{G} F_G(\lambda_W, \lambda_G) + \alpha_{a2} F_{CA}(\lambda_W, \lambda_G)$$

where

$$\lambda_W = \frac{H_W}{H_T}; \lambda_G = \frac{H_G}{H_T}; \alpha_{a2} = \frac{p_{a2}}{\rho_w g H_T}; \alpha_{G} = \frac{\rho_G}{\rho_w};$$

$$F_{CA}(\lambda_W, \lambda_G) = (1-2\lambda_W - \lambda_G) \ln \frac{1-\lambda_W - \lambda_G}{1-2\lambda_W - \lambda_G};$$

$$F_G(\lambda_W, \lambda_G) = \lambda_W \lambda_G$$

To these equations an additional relation between the tower heights $H_T$ and its components $H_G$, $H_W$ and $Ha2$ should be considered named geometrical-compatibility relation:
or in dimensionless form:

\[ 1 - 2\lambda_W - \lambda_G = \lambda_{a2} \geq 0 \]

where

\[ \lambda_{a2} = \frac{H_{a2}}{H_T}; \lambda_G = \frac{H_G}{H_T}; \lambda_W = \frac{H_W}{H_T} \]

So, for a GCAHPT the parameters \( \lambda_W \) and \( \lambda_G \) should be satisfied the following compatibility condition:

\[ \lambda_G \leq 1 - 2\lambda_W; \lambda_W \leq \frac{1}{2}(1 - \lambda_G) \]

The compatibility condition as equality (i.e. \( H_{a2} = H_T - 2H_W - H_G = 0; 1 - 2\lambda_W + \lambda_G = 0 \)) corresponds to the upper limit of the gravity-based storage when the compressed air missing (\( H_{a2} = 0 \)). This maximum limit capacity can be expressed as follow:

\[
\frac{E_{GHPT-limit}}{\rho_G g A_T H_T^2} = \alpha_G F_{G-limit}(\lambda_W, \lambda_G) \\
\text{where} \\
\alpha_G = \frac{\rho_G}{\rho_W}; \ F_{G-limit}(\lambda_W, \lambda_G) = \lambda_W (1 - 2\lambda_W)
\]

Based on the equations can be make the statement that for a given tower height \( H_T \) the stored/produced energy of GCAHPT depend form the overload piston height \( H_G \) through the dimensionless parameter \( \lambda_G = H_G / H_T \), from the water height \( H_W \) through the dimensionless parameter \( \lambda_W = H_W / H_T \) and from the air part height \( H_{a2} \) through the dimensionless parameter \( \lambda_{a2} = H_{a2} / H_T \). This dependence is expressed through the function \( F_{CA}(\lambda_W, \lambda_G) \) which represent the compressed-air-based storage/production and through the function \( F_G(\lambda_W, \lambda_G) \) which represent the gravity-based storage/production both integrated in GCAHPT.

For performing of comparative analysis regarding the weighting of both components of GCAHPT (GHPT, CAHPT) a good tool can offer graphical representations of the functions \( F_{CA}(\lambda_W, \lambda_G) \) and \( F_G(\lambda_W, \lambda_G) \) considering the parameter \( \lambda_G = H_G / H_T \) as abscissa-axis variable and taking representative values for parameter \( \lambda_G = H_G / H_T \). The compressed air-storage function \( F_{CA}(\lambda_W, \lambda_G) \) is represented above the abscissa-axis (0, \( \lambda_W \)). The considered values of parameter \( \lambda_G \) are 0.0; 0.1; 0.2; 0.3; 0.5; 0.75. In the legend the parameter \( \lambda_G \) for the curves \( F_{CA}(\lambda_W, \lambda_G) \) is noted as CA-\( \lambda_G \).

The gravity-storage function \( F_G(\lambda_W, \lambda_G) \) is represented under of the abscissa-axis (0, \( \lambda_W \)) for the same values of the parameter \( \lambda_G \). The curves are inclined straights in relation to variable \( \lambda_W \) having inclinations given by the same \( \lambda_G \) values as used above for the function \( F_{CA}(\lambda_W, \lambda_G) \) (figure 3). In the same graphic is represented also the function \( F_{G-limit}(\lambda_W, \lambda_G) \) (the curve with dotted line) which borders the validity domain according to the relation (9).
As examples for the application of calculation formula 5 as well as the graphics shown above several examples will be considered for representative sizes of the heavy overload piston namely \( \lambda_G = H_G / H_T = 0.1; 0.2; 0.3; 0.5 \) (i.e. a relatively small, middle and large heavy overload piston). For each case the energy storage performance of GCAHPT will be calculated for the following combination of characteristic parameters: tower height \( H_T \), heavy overload piston height \( H_G \) and his material density \( \rho_G \) and the maximum accepted air pressure \( p_{a2} \). In this regard consider a tower height of \( H_T = 10 \) m and an overload piston from steel with a mass density of \( \rho_G = 7.8 \times 10^3 \) kg/m\(^3\) and three value of maximum allowed air pressure namely \( p_{a2} = 2 \) bar, 4 bar and 8 bar.

On can see in figure 3 that for each \( \lambda_G \) correspond a maximum value of the function \( FCA \) for a certain value of the parameter \( \lambda_W \) (i.e. a certain value of water height in tower). These values are indexed with “max” namely \( \lambda_{WCA-max} \) and \( FCA-max \). Attention, do not confuse \( \lambda_{W-max} \) (the maximum value of \( \lambda_W \) on the abscissa-axis corresponding to an \( FCA \) graphic) with \( \lambda_{WCA-max} \) value at which the function \( FCA \) is max (see graphs in figure 3). The storage capacities can be expressed from (9). The pair of \( \lambda_{WFC-max} \) and \( FCA-max \) values may be determined from the graphics shown in Figure 3 for the given \( \lambda_G \) values.

In Table 2 are presented the numerical results for the above considered numerical dates putting into evidence the weighting of both gravity and compressed storage components.
Table 2. Numerical results for the specific storage performances ($e_{G\text{-max}}$, $e_{CA\text{-max}}$) and their weighting in $e_{GCA\text{-max}}$ for $H_f = 10\text{m}$ and $\rho_G / \rho_W = 7.8$

| $\lambda_G$ | $\lambda_{WCA\text{-max}}$ | $e_{G\text{-max}}$ | $e_{CA\text{-max}}$ | $p_{a2}$ [bar] | $\alpha_{pa}$ | $e_{CA\text{-max}}$ | $e_{GCA\text{-max}}$ | $e_{G\text{-max}}$ % | $e_{CA\text{-max}}$ % |
|------------|----------------|-------------------|-------------------|----------------|--------------|-------------------|-------------------|----------------|----------------|
| 0.0        | 0.35           | -                 | 0.232             | 2              | 2.04         | 0.473             | 0.473             | 0.0             | 100            |
|            |                |                   |                   | 4              | 4.08         | 0.946             | 0.946             | 0.0             | 100            |
|            |                |                   |                   | 8              | 8.16         | 1.892             | 1.892             | 0.0             | 100            |
| 0.1        | 0.32           | 0.250             | 0.209             | 2              | 2.04         | 0.426             | 0.676             | 37.0            | 63.0           |
|            |                |                   |                   | 4              | 4.08         | 0.853             | 1.103             | 22.7            | 77.3           |
|            |                |                   |                   | 8              | 8.16         | 1.705             | 1.955             | 12.8            | 87.2           |
| 0.2        | 0.30           | 0.468             | 0.183             | 2              | 2.04         | 0.373             | 0.841             | 55.6            | 44.4           |
|            |                |                   |                   | 4              | 4.08         | 0.747             | 1.215             | 38.5            | 61.5           |
|            |                |                   |                   | 8              | 8.16         | 1.493             | $1.961$           | 23.9            | 76.1           |
| 0.3        | 0.25           | 0.585             | 0.162             | 2              | 2.04         | 0.330             | 0.915             | 63.9            | 36.1           |
|            |                |                   |                   | 4              | 4.08         | 0.661             | $1.246$           | 47.0            | 53.0           |
|            |                |                   |                   | 8              | 8.16         | 1.322             | 1.907             | 30.7            | 69.3           |
| 0.5        | 0.18           | 0.702             | 0.116             | 2              | 2.04         | 0.237             | 0.939             | 74.8            | 25.2           |
|            |                |                   |                   | 4              | 4.08         | 0.473             | $1.175$           | 59.7            | 40.3           |
|            |                |                   |                   | 8              | 8.16         | 0.947             | 1.649             | 42.6            | 57.4           |

Based on the numerical results from Table 2 it can be observed, as expected, that the weighting of the compressed-air based storage ($e_{CA\text{-max}}$) is even greater as the overload piston is smaller and substantially increase with increasing final air pressure $p_{a2}$. For example, for a usual value of working pressure of $p_{a2}=4\text{ bar}$ the weighting of compressed air-storage ($e_{CA\text{-max}}$) increases from 40.3% for $\lambda_G = 0.3$ (i.e. $H_G = 3\text{m}$) to 77.3% for $\lambda_G = 0.1$ (i.e. $H_G = 1\text{m}$). According to this the weighting of gravity-based storage ($e_{G\text{-max}}$) decreases from 59.7% to 22.7%.

Generally, the formulas (5) and the diagrams in figure 3 presented above allow the analyze of a GCAHPT performance for any combination of system parameters. Also, if are given the basic parameters $p_{a2}$ and $H_f$ one can analyze the dependence of the storage performance for any combination of the overload piston height (through $\lambda_G=HG/HT$) and water height (through $\lambda_G=HG/HT$) and so can be performed the sizing and optimization of the GCAHPT.

For large electrical production plants like photovoltaic and wind parks the GCAHPT analyzed in the present paper can be used also as high capacity storage plant in the form of groups of power towers in the same way as the classical GHPT discussed in [6].

4. Conclusions

Starting from the finding that besides the many advantages of classical gravity-hydro-power storage (GHPTS), especially in the case of small plants, important disadvantages are the cost-intensive overload piston made of heavy material (e.g., steel which has a density of approximately 7.8 t/m³) and also the difficulty of transportation of several hundreds of tons of heavy objects such these heavy piston. The present study is focused on a power-tower storage system which can replace partial or total the heavy overload piston through a compressed air-based storage. The complete replacement with compressed air-based power tower storage (i.e. CAHPT – Storage System) was in detail presented in an earlier own paper [8].

In the present paper after a short overview of GHPT and CAHPT storage plants the Gravity-Compressed-Air-Hydro-Power-Tower-Storage (GCAHPT) is presented which integrate both Gravity-
based and Compressed Air-based storage technique in a power tower. A theoretical basis embodied in formulas and diagrams is presented which allow the analyse of the combined influence of both compressed air pressure and heavy overload lifting/falling piston in the tower on the stored energy performance of GCAHPT. So, for the given basic parameters like maximum allowed air pressure in the tower and tower height, the dependence of the storage performance of the GCAHPT from the overload piston height and from water height in the tower can be analysed and on this basis can be performed the sizing and optimization of a GCAHPT.

Also, examples of calculations regarding the weighting of the gravity-based and compressed-air-based storage are presented, in the form of tables, considering representative combinations of the characteristic parameters of the GCAHPT as well.

For large electrical production, the plants like photovoltaic and wind parks the GCAHPT analyzed in the present paper can be used also as high capacity storage plant in form of groups of power towers in the same way as the classical GHPT.

References

[1] X. Luo, J. Wang, M. Donner, J. Clarkr, “Overview of current development in electrical energy storage technologies and the application potential in power system operation”, *Applied Energy*, Volume 137, Pages 511-536, January 2015.

[2] S. Rehman, L.M. Al-Hadhrami and M. Alam, “Pumped hydro energy storage system: A technological review”, *Renewable and Sustainable Energy Reviews*, Volume 44, pp 586-598, April 2015.

[3] B. Moris, “Underground pumped hydro energy storage at grid scale”, [Online] 2011 [Accessed 22. 01. 2020] Available at: https://polizeros.com/2011/04/26/underground-pumped-hydro-energy-storage-at-grid-scale

[4] T. Schueneman, Gravity Power Module Revolutionizes Pumped Hydro Energy Storage. [Online] 2011 [Accessed 22. 01. 2020] Available at: https://www.triplepundit.com/2011/03/gravity-power-module-aims-revolutionize-pumped-hydro-energy-storage.

[5] Gravity Power. Grid Scale Energy Storage [Online] 2017 [Accessed 22. 01. 2020] Available at: http://www.gravitypower.net.

[6] V. Neisch, R. Klar, M. Aufleger, „Powertower – Hydraulischer Energiespeicher”, *12. Symposium Energieinnovation*, Graz/Austria, pp 1-12, 2012.

[7] Bi, J., Jiang, T., W., Ma, X. Chen, “Research on Storage Capacity of Compressed Air Pumped Hydro Energy Storage Equipment”, *Energy and Power Engineering*, 5, 26-30, 2013.

[8] I. David, I. Vlad, and C.M. Stefănescu, “Replacement possibilities of the heavy overload piston of gravity- hydro-power-tower energy storage plants Using compressed air”, July 2018, *18th International Multidisciplinary Scientific GeoConference*, SGEM, Bulgaria, 2018.