ORIGINAL PAPER

RETROFITTING WATER TOWERS FOR HYDROELECTRIC POWER GENERATION

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Abstract. *This paperwork is focused on highlighting the potential of reusing the local decommissioned water towers, to serve as hydroelectric energy buffers, on demand. It is a known fact that most water towers, worldwide, built either for municipality community or for industrial service, are left to decay, destroyed, or even converted as landmarks, restaurants and lodgings, due to the upgrade to a modern water distribution system.*

Keywords: *water tower, hydroelectric, power, generation, renewable energy.*

1. INTRODUCTION

Since ancient times, water towers were built in various forms and sizes, ranging from a height of several meters to hundreds of meters, with a diameter of few meters to tens of meters and with a storage capacity of tens to even millions of cubic meters. The purpose of these so called „water tanks", was to provide a constant water flow rate at a certain pressure, by using the hydrostatic pressure principle, in the early water distribution piping, for domestic and industrial use, as drinking water, fire extinguishing or sewage water. Often, a pumping system was used to fill back the water tank, after drainage. The filling and draining cycle also prevented the water from the tower to freeze during the winter time.

Nowadays, some water towers still serve their purpose in remote areas, where the modern water distribution system is either too expensive or too far to deploy.

On the other hand, the decommissioned ones are highly overlooked by the state municipalities or private stakeholders, either from lack of interest, vision or funds, thus ending up as rubble due to demolition, as arhitectural landmarks, as dwellings, or even worse, as cellular towers.

From the electrical point of view, water towers can be considered a type of *pumped hydroelectric energy storage systems* (PHES) and can be used for electrical load balancing during the periods of peak demand for electrical energy [1].

The best advantage of the water towers is that they can have different or multiple water intake sources: either from lakes and rivers, groundwater, underground reservoirs and wells, from the local water distribution network or even from rain, in some particular areas.

Another advantage of the water tower resides in its basic constructive concept [2], as it only needs: a source of water (that can be recirculated in some cases), a pump for feeding the water through its inlet pipe, an overflow pipe/valve to prevent the overflow of the water, a storage tank, an outlet pipe for water evacuation and a valve to regulate the inlet/outlet water flow.

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The PHES can be used as additional electrical generators in a microgrid, in conjunction with the other more common, *renewable energy sources* (RES), such as the wind and photovoltaic generators [3], for a sustainable low CO_2 footprint [4].

Because of their radial shape, water towers can also be equipped with photovoltaic panels or small wind turbines, to further maximise the renewable energy exploitation potential at low costs.

2. MATERIALS AND METHODS

In the typical configuration (Fig. 1), the water is pumped and stored in the tank, by a high pressure water pump, while an electromechanical or manual valve releases the water to consumers, when it's needed.

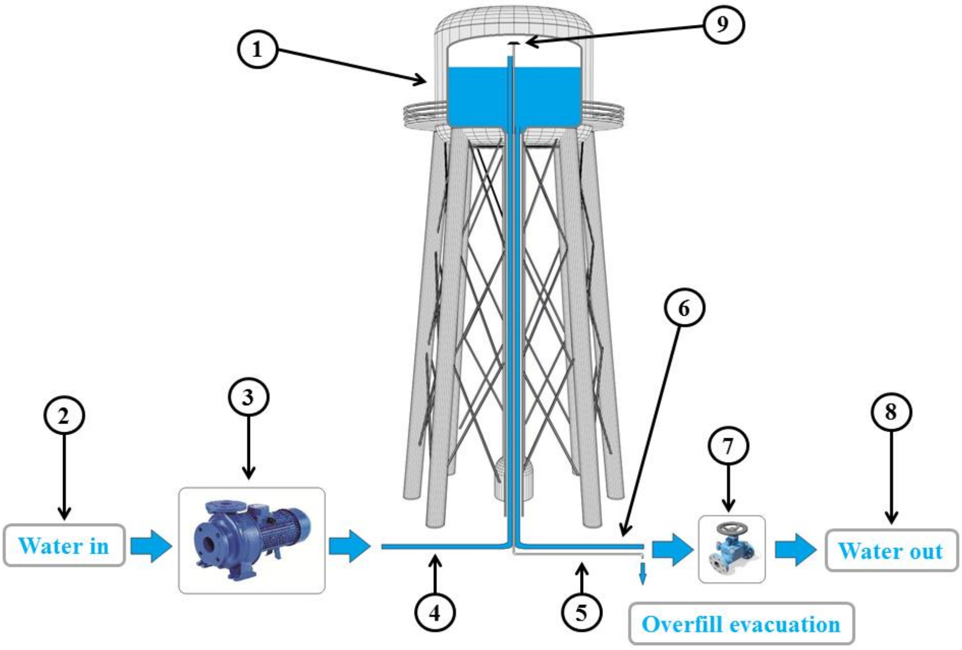

Figure 1. Typical water tower layout: 1-water tank, 2-water source, 3-water pump, 4-water inlet pipe, 5-tank overfill/pressure evacuation pipe, 6-water outlet pipe, 7-water regulation valve, 8-water distributed to consumers, 9-tank overfill level cap valve.

As the proposed water tower system already has the basic components installed, such as the water pump and the valve regulator, in order to convert it to an electric power generation entity, there are some minimal investments to make the upgrade (Fig. 2), such as:

- 3 phase water turbine generator;
- AC to DC regulator;
- DC to AC inverter;
- industrial PLC with RTC;
- power relays, wiring and junction box.

There are two configurations in which the upgraded water tower can operate in emergency cases, according to its storing capacity and hydroelectric output power:

- as a standalone off-grid backup generator (for an output < 10kWh/day);
- as an additional on-grid generation entity (for an output > 10kWh/day).

In both configurations, the water tower can be exploited, through the programmable logic controller, to generate hydroelectric energy in the electric grid, either on demand, or on pre-programmed hours (by a real time clock):

- at ***night-time***, when solar energy is not available (***in the off-grid configuration***) – then refill the tank during daytime, when excess of solar energy is available;
- at ***daytime***, when the electric energy demand curve is at peak (***in the on-grid configuration***) – then refill the tank during night-time, when the electrical energy (kWh) is cheaper.

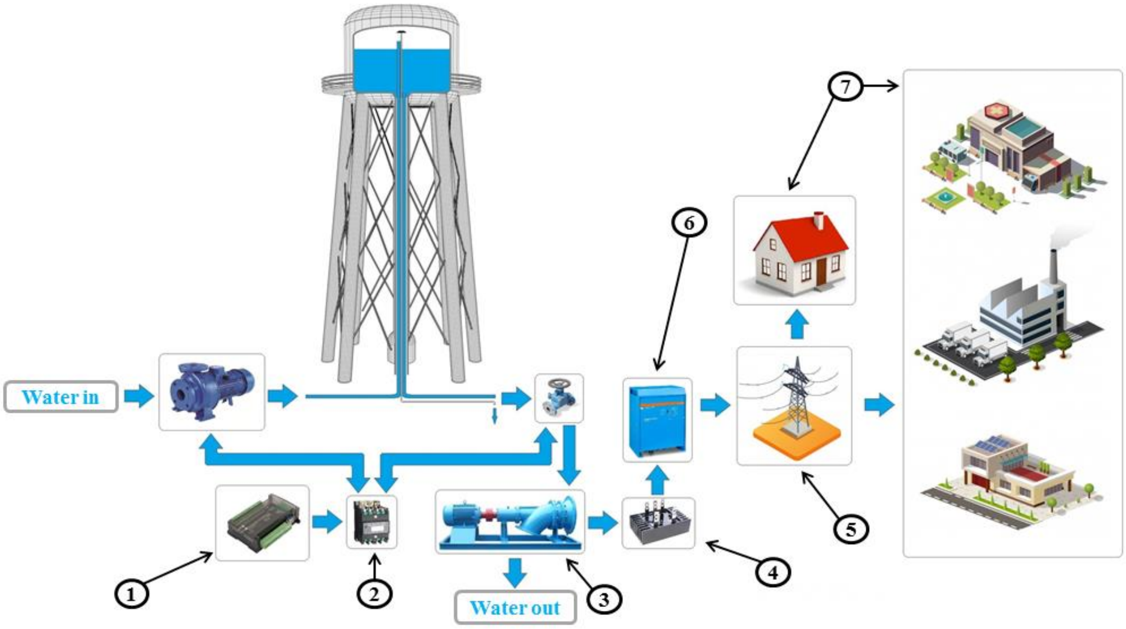

Figure 2. Proposed water tower layout: 1-industrial PLC, 2-power relays, 3-hydroelectric power generator, 4-AC to DC regulator, 5-electrical grid, 6-DC to AC inverter, 7-consumers.

To have a full comprehensive view over the potential of our proposed hydroelectric system upgrade, a theoretical calculus is required. The system dimensioning implies both the calculation of the components energy conversion efficiency, the electrical power ratings correlated with time, and the water flow correlated with the usable water tower volume.

A theoretical system example with the required physical and electrical parameters of components available on the market, is presented in Table 1, in order to conduct further calculations.

Table 1. Components technical data.

System component	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
Water tower	*height:30.5 m*	*volume:460* m^3	*head: 20 m*	*NA*	*NA*
Water pump	*power input:2 kW*	*flow rate:0.0041* m^3/s	*head: 29.6 m*	*speed: 2600 rpm*	*NA*
Electric generator	*power output: 8 kW*	*flow rate:0.064* m^3/s	*head: 20 m*	*cos phi: 0.8*	*efficiency: 88%*
Turbine	*Turgo*	*NA*	*NA*	*NA*	*efficiency: 92%*
Inverter	*power output: 8 kW*	*AC voltage output: 220 V/230 V/240 V*	*AC phase: 1/3*	*frequency: 50/60 Hz*	*efficiency: 98%*
Regulator	*AC input*	*DC output*	*AC phase: 3*	*NA*	*efficiency: 91%*
PLC	*RTC*	*TTL*	*GPIO*	*USB/WiFi*	*industrial: yes*
Relays	*P rating: 5 kW*	*U rating: 250 V*	*I rating: 20 A*	*cycles: 18000*	*industrial: yes*

3. RESULTS AND DISCUSSION

The theoretical hydroelectric group efficiency of power conversion, is determined with relation (1) as follows:

$$\begin{aligned} \eta_{HG} &= \eta_{Gen} \times \eta_{Turb} \\ \eta_{HG} &= 88\% \times 92\% \\ \eta_{HG} &= 80\% \end{aligned} \tag{1}$$

where η_{HG} is the combined hydroelectric group efficiency, η_{Gen} is the electric generator efficiency and η_{Turb} is the turbine efficiency.

The theoretical hydroelectric power generated by falling water from the tower, through the hydrogenerator, can be expressed as (2):

$$\begin{aligned} P_{th} &= g \times H \times \rho \times Q \times \eta_{HG} \times pf \\ P_{th} &= 9.81 \times 20 \times 1000 \times 0.064 \times 0.8 \times 0.8 \\ P_{th} &= 8036 \text{ W} \end{aligned} \tag{2}$$

where P_{th} is the theoretical hydroelectric power output, g is the gravitational acceleration of 9.81 m/s^2, H is the head point of the falling fluid of 20 m, ρ is the water density of 1000 kg/m^3, Q is the volumetric flow rate of 0.064 m^3/s, η_{HG} is the global efficiency of the hydroelectric group (electric generator and turbine combined) of 80% and *pf* which represents the *cos phi* power factor of the motor, with 0.8 typically.

Furthermore, there is also necessary to calculate the regulator and the inverter efficiencies in order to have a correct result over the losses and the output power delivered to the grid, as (3, 4):

$$\begin{aligned} P_{Reg} &= P_{th} \times \eta_{Reg} \\ P_{Reg} &= 8036W \times 91\% \\ P_{Reg} &= 7.3 \text{ kW} \end{aligned} \tag{3}$$

where P_{Reg} is the output power of the regulator after AC to DC conversion and η_{Reg} is the efficiency of the regulator, while:

$$\begin{aligned} P_{Inv} &= P_{Reg} \times \eta_{Inv} \\ P_{Inv} &= 7.3kW \times 98\% \\ P_{Inv} &= 7.1 \text{ kW} \end{aligned} \tag{4}$$

where P_{Inv} is the output power of the inverter after DC to AC conversion and η_{Inv} is the efficiency of the grid inverter.

Of course, other electric and hydraulic losses might occur in the final system, resulting in a drop of 2% to 4%, from the total electrical power output.

The required time for filling and draining the water tank is described in Table 2.

Table 2. Time estimations for filling/emptying the water tower.

System component	**Flow rate**	**Time required to fill the tank (460 m^3)**	**Time required to drain the tank (460 m^3)**
Water pump	*0.246 m^3/min (0.0041 m^3/s)*	*1869.91 min* ***(31.16 h)***	*NA*
Hydroelectric generator	*3.84 m^3/min (0.064 m^3/s)*	*NA*	*119.79 min* ***(1.99 h)***

The hydraulic power of the water pump is expressed as (5):

$$P_{hWP} = \frac{Q \times \rho \times g \times H}{3.6 \times 10^6 \, J / kWh}$$

$$P_{hWp} = \frac{14.76 \times 1000 \times 9.81 \times 29.6}{3600000} \tag{5}$$

$$P_{hWP} = 1.19 \text{ kW}$$

where P_{hWP} is the hydro power, Q is the volumetric flow rate of 14.76 m^3/h, ρ is the water density of 1000 kg/m^3, g is the gravitational acceleration of 9.81 m/s^2 and H is the head point of the pumped fluid of 29.6 m.

Thus, we can calculate the shaft power with relation (6):

$$P_S = \frac{P_{hWP}}{\eta}$$

$$P_S = \frac{1.19 kW}{0.8} \tag{6}$$

$$P_S = 1.48 \text{ kW}$$

where P_S represents the shaft power, P_{hWP} is the hydo power of the water pump of 1.19 kW and η is the pump efficiency of 0.8.

In conclusion, the total potential energy capacity of the water tank is calculated in (7):

$$E_P = \frac{V \times \rho \times g \times H}{3.6 \times 10^6 \, J / kWh}$$

$$E_P = \frac{460 \times 1000 \times 9.81 \times 20}{3600000} \tag{7}$$

$$E_P = 25.07 \text{ kWh}$$

where E_P is the total energy potential stored in the water tower, V is the water tower usable volume of 460 m^3, ρ is the water density of 1000 kg/m^3, g is the gravitational acceleration of 9.81 m/s^2, H is the head point of the falling fluid of 20 m.

The total energy production of the hydroelectric system is computed in (8):

$$E_{HES} = P_{Inv} \times \left(\frac{V}{Q \times t} \right)$$

$$E_{HES} = 7.1kW \times \left(\frac{460}{0.064 \times 3600} \right) \quad (8)$$

$$E_{HES} = 14.17 \text{ kWh}$$

where E_{HES} is the total energy produced by our proposed hydroelectric system with one full water tank, P_{Inv} is the output power delivered by the inverter to the electrical grid of 7.1 kW, V is the water tower usable volume of 460 m^3, Q is the volumetric flow rate of 0.064 m^3/s and t is the time expressed as 3600 seconds or 1 hour.

4. CONCLUSIONS

As we can observe in the previous calculations, the major power losses occur each time when power is converted from one component to another and from one form to another. From the total of 25.07 kWh energy potential of the water tower, 43% of it represents hydraulic, mechanic and electric losses. The proposed hydroelectric energy production system, in its current form, cannot replace the more performant ones based on photovoltaic panels, wind turbines or biofuel generators, but it can provide a far more ecological and cheaper alternative to the classic energy storage systems based on lead-acid or lithium ion batteries.

The hydroelectric system can work together with the other renewable energy production systems in a meshed electrical grid, as an electrical power buffer, for the daily energy demand curve, or as a backup generator in islanded electrical grid infrastructures, typically in small towns or isolated households. The upgrade costs can reach to 2/3 of a typical off-grid photovoltaic system with battery storage and it can further be upgraded with photovoltaic panels in accordance with the water tower shape and total surface.

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