# Preliminary Performance Evaluation of a Ground-Level Integrated Diverse Energy Storage (GLIDES) Prototype System[1]

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## ABSTRACT

Increased generation capacity from intermittent renewable electricity sources being brought on-line combined with an electrical grid ill-equipped to handle the mismatch between electricity generation and use, necessitates advanced bulk energy storage technologies. This paper introduces once such technology, GLIDES (Ground-Level Integrated Diverse Energy Storage), which stores energy by compressing/expanding a gas (air) using a liquid (water) piston. A Pelton turbine is utilized as the energy extraction machine through which high head water is passed. This paper is the first to report on experimental system performance of the GLIDES technology.

***Keywords***: energy storage, compressed air, micro pumped-hydro storage, near-isothermal expansion/compression

## 1 INTRODUCTION

Currently, pumped-storage hydroelectricity and compressed air energy storage are used for grid-scale energy storage [1], and batteries are used at smaller scales [2]. However, prospects for expansion of these technologies are undermined by a number of challenges including, but not limited to, geographic limitations (pumped-storage hydroelectricity and compressed air energy storage) [3], low roundtrip efficiency (compressed air energy storage) [4], and high cost (batteries) [2]. In addition to the above, pumped-storage hydroelectricity and compressed air energy storage are challenging to scale-down [4], while batteries are challenging to scale-up [2]. Similar to compressed air energy storage, the storage technology presented here is based on air compression/expansion. However, several novel features lead to near-isothermal processes, higher efficiency, greater system scalability, and the ability to site a system anywhere [5]. GLIDES (Ground-Level Integrated Diverse Energy Storage) stores energy by compressing/expanding a gas (air) using a liquid (water) piston. The concept was recently introduced and extensively studied analytically [5,6]. With the use of the liquid piston, GLIDES replaces the inefficient gas turbomachines used in conventional gas compression/expansion systems with high efficiency hydraulic machines. Promising results from physics based numerical system performance simulations [5] led to the development of a 2 kWh proof of concept prototype system built at Oak Ridge National Laboratory (ORNL). When electricity is inexpensive or available from renewables, a high efficiency pump is used to pump a liquid inside one or more pressure vessels which have been pre-pressurized with a gas. As the liquid level rises, the gas is further pressurized and energy is stored. This charging process continues until electricity is no longer available, or the maximum allowable pressure is reached. When the stored energy is needed, the pressurized gas is allowed to expand, pushing the high pressure water out of the vessel and through a high efficiency hydraulic turbine coupled to an electrical generator to dispatch electricity. Furthermore, if low to medium temperature waste heat (for example, from the condensers of air-conditioning systems, solar-thermal hot water receivers, combined heat and power systems, geothermal wells, or waste heat exhaust from turbines or stacks) is available, it can be dispatched to further boost the gas pressure, increasing the amount of energy available.

## 2 PROTOTYPE DESCRIPTION

### 2.1 Description of Components

A first lab-scale prototype of the GLIDES system has been built, and initial experimental tests have been conducted. Figure 1 shows a schematic of the GLIDES prototype system. There are four major components: an atmospheric pressure water storage tank, high pressure vessels, a pump/motor assembly, and a turbine/generator assembly. The system is connected through a piping assembly which consists of piping, valves, and fittings. Prior to operation, the system is initially pressurized with compressed air to the minimum working pressure in a one-time process. In charging mode, the positive displacement pump pushes liquid into the pressure vessels, compressing the gas and increasing the pressure until the maximum working pressure is reached. In discharging or power-

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delivery mode, one or both of the control valves are opened and the now high pressure gas pushes the liquid out of the pressure vessels through the Pelton turbine which spins the generator and dispatches electricity. This can be seen in Figure 1 which shows charging and discharging modes with the liquid flow path highlighted in red. For the prototype system, four 500 liter pressure vessels with maximum allowable pressure of 160 bar are used. An 11 kW, 35 L/min motor/pump assembly and 5 kW, single phase, 120 VAC, 60 Hz electrical generator are used. The first GLIDES prototype produces approximately between 700 W and 2 kW of power over a period of about 40 minutes, when operated with one Pelton turbine jet. This output is doubled when operated with the additional jet. Figure 2 shows images of the prototype system installed at ORNL.

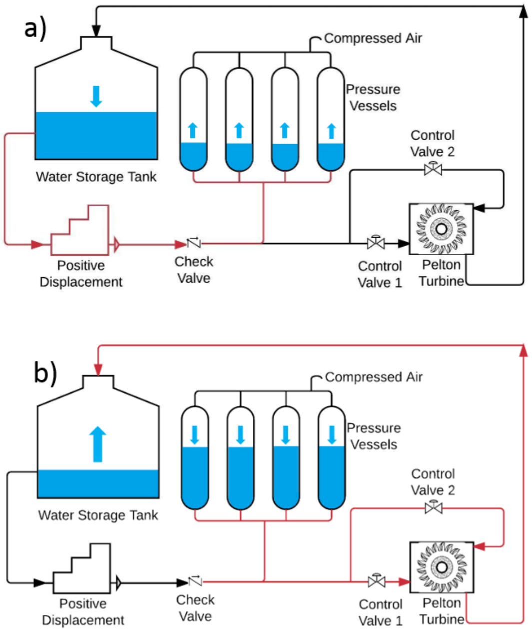

Figure 1: GLIDES prototype schematic during a) charging and b) discharging

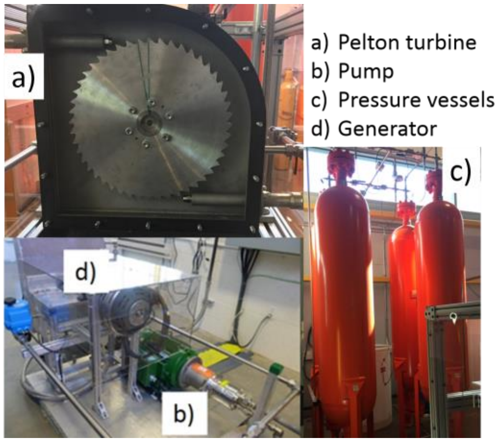

Figure 2: GLIDES system components

## 2.2 Instrumentation, Controls, & Data Acquisiton

Several instruments were installed to capture the performance of the system. In the pressure vessels, eight thermocouples and four pressure transducers were installed to measure temperature and pressure. For each pressure vessel, one thermocouple was installed at the top and bottom to measure gas and liquid temperatures, respectively. The four pressure transducers were installed at the top of the pressure vessels to measure gas pressure. A water level transducer was installed inside of the atmospheric pressure water storage tank; this measurement was used to calculate charging/discharging flowrates and gas volume inside of the pressure vessels. Watt transducers were installed on the charging pump and the electrical generator to measure the system power input and output. A torque meter was installed between the turbine and generator shafts to measure torque and shaft speed. Thermocouples were also added to measure the ambient air temperature and water temperature inside the atmospheric pressure water storage tank. All instrumentation was calibrated across the full expected ranges of measurements according to NIST traceable calibration procedures. A controls and data acquisition system utilizing National Instruments LabVIEW software and hardware was used to control the system and log measurements.

# 3 RESULTS

## 3.1 Thermodynamic Performance

The following results are for a single GLIDES test run. The system was charged from 70 bar to 130 bar pressure and then allowed to equilibriate during a pause period lasting approximately 5 hours between the end of charging and the beginning of discharging. Discharging occurred with one Pelton turbine jet until all of the water that was pumped during the charging period was discharged.

Figure 3 shows the transient air and water temperatures and air pressure through the duration of the test. Both the air and water temperatures are initially at 21°C. As charging begins and water is pumped into the pressure vessels, the temperature of the air begins to increase as it is compressed by the water below. It increases to a maximum of 35°C when charging is completed, after which it decreases during the pause period as heat is lost to ambient through the vessel walls. Pressure behaved similarly, increasing from 70 bar to 130 bar, and then some pressure is lost during the pause period due to the drop in temperature from heat loss.

During discharge, the temperature of the air drops as water is forced out of the pressure vessels and the air expands. The rate of change (slope) of the temperature decreases during discharge. This behavior can be attributed to heat transfer into the air from the now warmer ambient, through the vessel walls. This heat transfer counteracts and slows the cooling due to expansion. Another pause period follows discharge as the system temperatures are allowed to return to equilibrium with ambient.

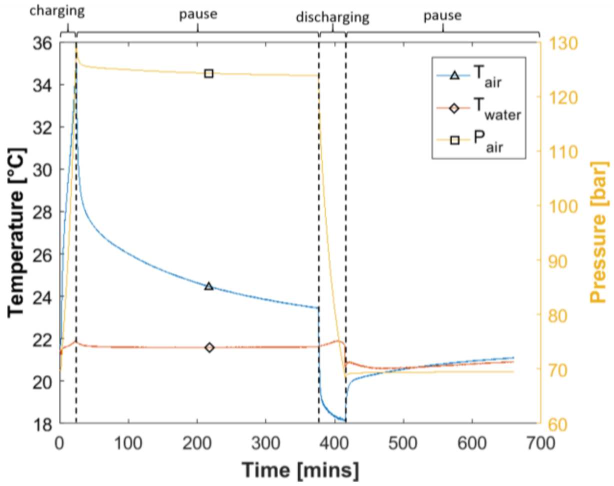

Figure 3: Air/water measured transient temperature and pressure profiles during GLIDES operation

The pressure-volume diagram of the air during the test run can be seen in Figure 4. The process begins at state point 1 (70 bar, ambient temperature). When charging begins, the pressure increases and the volume decreases until charging is completed at state point 2 (130 bar). At this point, the pause period begins as the system moves to state point 3. The volume remains constant, but pressure decreases due to temperature decrease accompanying heat loss.

The third process is discharge. As water is discharged from the vessels, the gas expands resulting in a pressure decrease and volume increase, until all the water is discharged from the vessels at state point 4. In the final process, the system is left idle, and the system returns to the initial state. Pressure increases as the temperature of the air rises back to the ambient temperature.

The indicated work input can be calculated by integrating (area under curve) the pressure-volume diagram from state 1 to state 2; the same can be done for state 3 to 4 for the indicated work output. The indicated storage efficiency is the ratio of this output to input. The area inside of the curve is lost work due to non-isothermal expansion/compression.

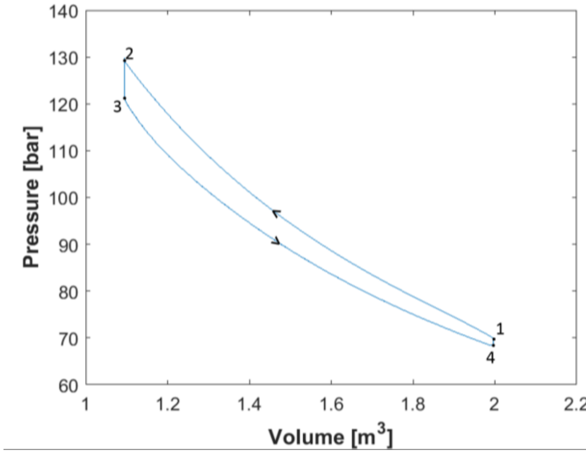

Figure 4: Pressure-volume diagram of GLIDES air

## 3.2 Charging (Energy Storage)

In Figure 5, the input indicated (thermodynamic) power and electric power to the charging pump during energy storage (charging) are shown. The indicated power is defined as the pressure times the flow rate, while the electric power is the electric power consumed by the pump-motor, as measured by a watt transducer. The difference between the two curves is power loss in the pump and electrical motor.

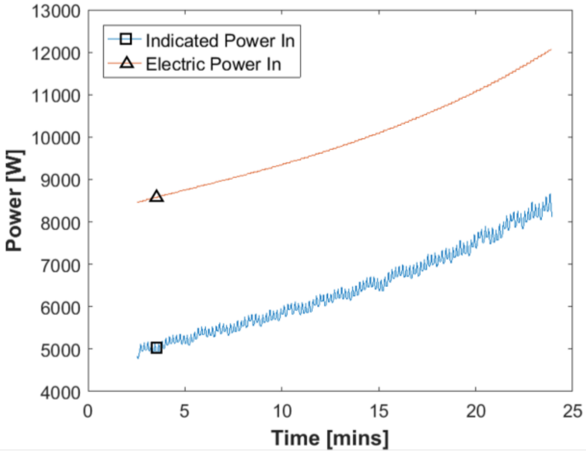

Figure 5: Power inputs to GLIDES system

This lost power can also be shown as the pump efficiency (indicated power divided by electric power) which is plotted in Figure 6. The pump efficiency ranges from a minimum of 60% to a maximum of 70%.

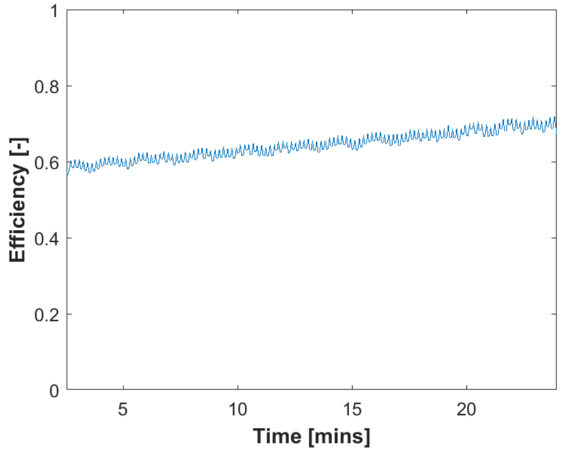

Figure 6: GLIDES charging pump efficiency

## 3.3 Discharging (Energy Recovery)

Figure 7 shows the indicated, shaft, and electric power outputs from the GLIDES system during energy recovery. The indicated power is the product of pressure and flow rate, the shaft power is the torque times the shaft speed (measured by the torque meter), and the electric power is the electricity generated by the electric generator (measured by the watt transducer). The power outputs decay in time due to the air pressure in the vessels decreasing as the air expands. The difference between the indicated power and the shaft power is power loss in the Pelton turbine, while the difference between the shaft power and the electrical power is due to power loss in the electric generator. The energy densities (indicated, shaft, and electrical) – the ratio of the energy output to the initial volume of air – are calculated to be 1.18, 0.55, and 0.39 kWh/m$^3$, respectively.

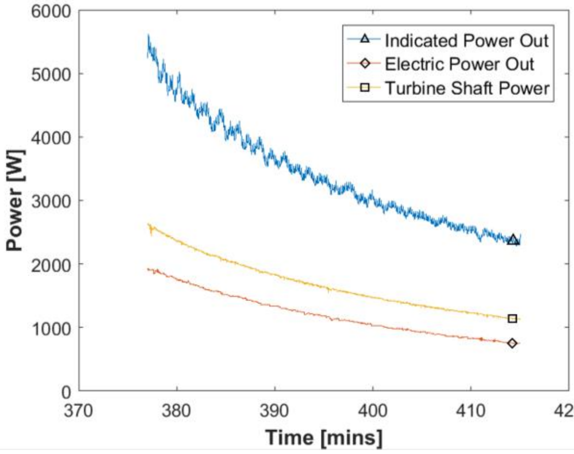

Figure 7: Power outputs from GLIDES system

The lost power in the turbine and generator are correlated to the turbine and generator efficiencies, which are shown in Figure 8. The turbine efficiency remains fairly constant throughout discharge at an average about 50%, while the generator efficiency decays slightly throughout discharge from a maximum of 75% to a minimum of 68%.

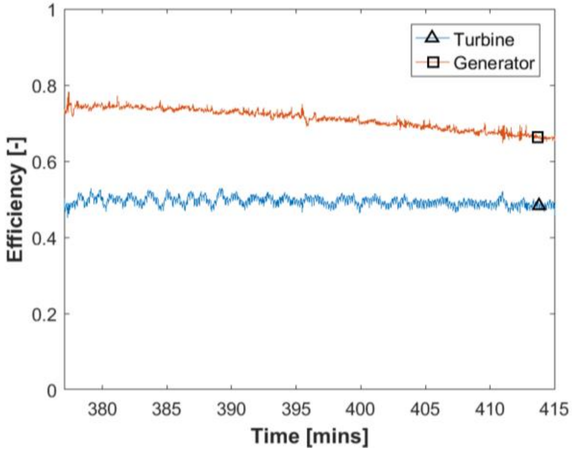

Figure 8: GLIDES turbine and generator efficiencies

### 3.4 System Efficiency and Losses

By accounting for the energy inputs and outputs, the losses throughout the various system components can be characterized and itemized, as shown in the pie chart in Figure 9. The electrical roundtrip efficiency (RTE), defined as the ratio of the electrical power output to the electrical power input, is calculated to be 21%. A small amount of energy (5%) is lost due to non-isothermal expansion/compression as heat is transferred to and from the air. The vast majority of energy losses occur in the Pelton turbine (29%) and pump (36%). In the generator, 8% of the energy is lost.

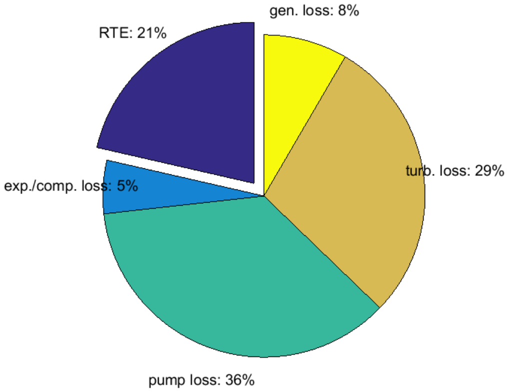

Figure 9: GLIDES roundtrip efficiency and losses

## 4 CONCLUSIONS

GLIDES is an energy storage concept which stores energy by compressing and expanding air via a liquid piston. Energy is stored by hydraulicly pumping water into one or several pressure vessels that have been pre-pressurized with air. The stored energy is recovered by passing the now high-head water through a hydraulic (Pelton) turbine which is coupled to an electric generator and discpatches electricity. This storage concept benefits from several advantages including, but not limited to, scaleability, terrain independence, and high efficiency. A first-ever, proof-of-concept prototype was designed, built, and tested at Oak Ridge National Laboratory which achieved roundtrip efficiency of 21% and electrical energy density of 0.39 kWh/m$^3$. The relatively low roundtrip efficiency can be attributed to poor energy conversion efficiency in the pump and turbine. For the proof-of-concept, off-the-shelf hydraulic machines were selected. With appropriate sizing/design, component efficiencies for future iterations can be significantly increased. In addition, larger GLIDES systems would benefit from improved efficiency of larger scale components.

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