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Pumped Storage Hydropower Augmented with Pressurized Air: The Ground-Level Integrated Diverse Energy Storage (GLIDES) System

GLIDES System Configurations and Use Cases

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The U.S. electricity system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. While increasing deployment of variable renewables such as wind and solar have enabled low-cost, clean energy in many U.S. regions, it also creates a need for resources that can store energy or quickly change their operations to ensure a reliable and resilient grid. Hydropower (including PSH) is not only a supplier of bulk, low-cost, renewable energy, but a source of grid-scale flexibility and a force-multiplier for other renewable power generation sources. Realizing this potential requires innovation in several areas: incorporating new operations into planning and licensing decisions, predicting new operations and management (O&M) patterns and costs to prevent unplanned outages, and designing new turbines and control systems for fast response and frequent ramping while maintaining high efficiency.

In April 2019, DOE's Water Power Technologies Office (WPTO) launched the HydroWIRES Initiative[1] to understand, enable, and improve hydropower and pumped storage hydropower's (PSH) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. The unique characteristics of hydropower, including PSH, make it well-suited to provide a range of storage, generation flexibility, and other grid services to support the cost-effective integration of variable renewable resources.

HydroWIRES is distinguished in its close engagement with the DOE National Laboratories. Five National Laboratories—Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the HydroWIRES portfolio as well as broader DOE and National Laboratory efforts such as the Grid Modernization Initiative.

Research efforts under the HydroWIRES Initiative are designed to benefit hydropower owners and operators, ISO/RTOs, regulators, original equipment manufacturers, and environmental organizations by developing data, analysis, models, and technology R&D that can improve their capabilities and inform their decisions.

More information about HydroWIRES is available at https://energy.gov/hydrowires

[1] Hydropower and Water Innovation for a Resilient Electricity System ("HydroWIRES")

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Executive Summary

Energy storage is essential for cost-effective integration of variable renewable energy sources to support a low-carbon grid. It is also a key enabler of a modern grid infrastructure for demand management. However, several main challenges remain for different kind of energy storage technologies in grid scale deployment. Currently, the largest source of utility-scale storage and long-duration storage in the US is pumped storage hydropower (PSH). Prospect of growth in conventional PSH faces challenges that have limited its deployment over the last three decades, including high capital costs and long deployment timelines. Batteries have high energy densities and are the primary technology of choice for small-scale energy storage. Compressed air energy storage (CAES) is another large-scale energy storage technology, but there are few plants deployed worldwide. They suffer from their low round trip efficiency (RTE) due to the use of high-pressure air compressors.

To address some of the challenges associated with these various storage technologies, the Ground-Level Integrated Diverse Energy Storage (GLIDES) is a modular PSH technology that was invented in 2015 at Oak Ridge National Laboratory. It utilizes gas compression to store electric energy. GLIDES stores energy by compressing gas using a liquid piston in high-pressure vessels. In doing so the vessels act as the upper reservoir in conventional PSH. Initially, the vessels are filled with gas to a prescribed pressure. To store energy, GLIDES uses a hydraulic piston pump to pump water into the pressurized vessels. As the water volume increases inside the vessels, water acts as a hydraulic piston compressing the gas on top of it. This process can be thought of as pumping water from the lower reservoir to the higher reservoir in PSH, increasing the water head. To dispatch the stored energy, the high-head water in the vessel is discharge through a high head Pelton hydraulic turbine that is connected to an electric generator. Employing high-pressure vessels enables GLIDES to reach water heads ~10-80 times higher than conventional PSH, achieving ~40 times higher energy densities, and overcomes the geographic limitation of conventional PSH. Although its energy density is much lower than that of batteries, GLIDES holds the potential advantages of having long service life, ease of system integration and being less hazardous over batteries. GLIDES prospective scalability could make it suitable for wide range of applications from behind the meter storage in buildings to grid-scale storage. It also makes it suitable for installations in densely populated urban areas where energy storage is most needed and real estate is limited. Over the last 5 years, work has focused on increasing GLIDES' energy density, decreasing its initial capital cost of the system, and increasing its revenue potential. Several designs were developed and prototyped to verify and demonstrate the improvement in energy density. The latest prototype achieved energy density of 1.21 kWh/m^3. Our analysis showed that it could achieve up to 1.7 kWh/m^3 with a mixture of air and carbon dioxide as the gas being compressed.

Two lab-scale prototypes are currently operational at the ORNL campus in Oak Ridge, TN. GLIDES is a cost-effective, scalable, flexible storage system that can provide market potential revenue in joint energy and ancillary markets by providing several grid services including energy arbitrage, contingency operating reserve, and frequency regulation and potentially has a lifespan same as that of PSH (>40 years). GLIDES's modularity, energy density scalability, and environmental benignity position it well to mitigate many of the market and regulatory barriers faced by PSH, CAES and batteries. The main objectives of the project was to improve the technoeconomic potential of GLIDES and to explore its value proposition in different energy market segments.

Besides the typical energy storage applications, such as renewable firming and load shifting, GLIDES is uniquely suited to hydropower-based generation projects. Due to the unique nature of hydropower projects typically having multiple purposes (i.e. flood control, irrigation, navigation etc.) there can be necessary passage of water when generation is not required or at times when revenue from generation is sub-optimal. This loss of available energy negatively affects the economics of generation at such

facilities. It is expected that integration of a storage system with a hydropower plant will provide value in (a) facilities challenged by hourly, daily, and seasonal requirements to pass water at inefficient or equipment damaging operating conditions; (b) run-of-river facilities in which the timing of flow and must-run generation is not revenue-optimal; and (c) power system contexts where the localized need for grid services exists due to physical grid conditions or local market conditions.

Cost analysis was performed to identify large cost items. It was found that the cost of pressure vessels comprised approximately 90% of the overall hardware cost. Lower cost alternatives were investigated. It was found that pipe segments that are rated for high pressure are the lowest cost option. With pipe segment as pressure vessel, the estimated total GLIDES first hardware cost (including cost of pipe segments, cost of machinery and the cost of piping) ranges between 350 to 750 $/kWh for MW-scale GLIDES (Kassaee et .al. 2019). Carbon fiber pressure vessels was second lowest option with total first hardware cost ranging between 2,000 to 3,500 $/kWh. Carbon steel vessels was the highest cost option with total first hardware cost ranging between 4,600 to 8,000 $/kWh. Other unconventional alternatives were also explored. Underground reservoirs such as depleted oil/gas reservoirs, aquifers and caverns are all potential low-cost candidates. Abandoned oil pipelines are also an option for GLIDES. The cost of a GLIDES system that uses depleted oil/gas reservoir as the high-pressure storage was estimated to be 13.6 to 136.91 $/kWh (Kassaee et .al. 2019).

Technoeconomic analysis was performed to demonstrate the value proposition of GLIDES. Use cases were developed for small-, medium- and large-scale GLIDES systems. Each use case was developed to explore different revenue streams. The small-scale case simulated a 20-kW GLIDES system as a local market trading electricity with both the grid and buildings with PV generation. The model found that a local market GLIDES is profitable while saving the buildings on electric utility bills. The medium-scale use case simulated a GLIDES as storage for a PV-powered EV charging station. A reduced order model to calculate the optimal capacity of a GLIDES system based on the number of charging slots and the average daily rate of EV arrival. The large-scale case simulated GLIDES integrated with 4 cascaded RoR plants in Idaho Falls, Idaho. In this use case simulation, GLIDES can provides value to the plants by allowing them to participate in the grid services market. Four GLIDES systems, 1 MW/4 hours each, were integrated to the four RoR plants. The total first hardware cost of the 4 GLIDES systems was estimated to be almost $11.5M, and a payback period as low as 5 years is possible depending on the price profile of electricity.

GLIDES is currently in the commercialization stage. With a successful protype of GLIDES being operated in the laboratory, next steps include conducting an engineering study to take a deeper dive on the potential coupling of a run-of-river hydropower facility with GLIDES and potentially a full-scale demonstration pilot. Piloting an actual system is needed to de-risk the technology and transition from technology readiness level (TRL) 5 (Laboratory scale, similar system validation in relevant environment) to TRL 8 (Actual system completed and qualified through test and demonstration). As part of the commercialization efforts, the GLIDES team participated in the DOE Energy I-Corps Cohort 13. Through the program, the team conducted 70 interviews representing various stakeholders: electric utilities, research and development institutes, government, water authorities and energy projects developers. The interviews were aimed at understanding what pain points stakeholders have and how GLIDES, as an energy storage technology, can relieve those pain points. Through the insights we collected from those interviews, we determined that regulated vertically integrated utilities were GLIDES most favorable entry point to the energy market. At the time of writing this report, two entities had applied to license GLIDES.

Acronyms and Abbreviations

CAES	Compressed Air Energy Storage
DOE	U.S. Department of Energy
EnD	Energy density
EPRI	Electric Power Research Insitute
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission
GLIDES	Ground-Level Integrated Diverse Energy Storage
IEA	International Energy Agency
IHSS	Integrated Hydropower Plant-Storage System
LAES	Liquefied Air Energy Storage
LHS	Latin Hypercube Sampling
LMP	Locational Marginal Price
ORNL	Oak Ridge National Laboratory
PSH	Pumped Storage Hydropower
PV	Photovoltaic
RoR	Run of river
RTE	Round trip efficiency
TRL	Technology Readiness Level
USD	U.S. Dollar
USGS	United States Geological Service

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1.0 Introduction

Energy storage is a central piece in the efforts to modernize the electric grid, reduce cost of electricity to both utilities and end users, and to enable higher penetration of renewable energy technologies. Various technologies have been invented for energy storage with different degrees of maturity. An extensive review of the available energy storage technologies, their cost, performance and maturity is presented in (Aneke and Wang 2016; Mongird et al. 2019, Mongrid et al. 2020). Grid-scale electric energy storage in the US is dominated by pumped storage hydropower (PSH) with a share of approximately 95% of the total US operational capacity worldwide on a GW basis as of November, 2020 (Baca and John 2020). Other large-scale technologies have emerged recently.

CAES is a large-scale (MW-scale) storage that uses gas compressors to store energy in the form of compressed air in high-pressure reservoirs. The stored energy is dispatched by discharging the compressed air through gas turbine that drivers an electric generator. Conventional CAES uses natural caverns as the high-pressure storage vessels. Conventional CAES is, similarly to PSH, geographically limited by the availability of naturally occurring caverns (Budt et al. 2016). Above-ground CAES uses pressure vessels rather than caverns. Small scale prototypes of above-ground CAES have been built (Kantharaj, Garvey, and Pimm 2015; Luo et al. 2015). The RTE of CAES systems is in the 40-50% range (Luo et al. 2015). More advanced configurations of CAES have been investigated and were claimed to have significantly higher RTE (Hartmann et al. 2012).

Liquified Air Energy Storage (LAES) stores electric energy in the form of high-pressure low-temperature liquified air. Different possible configurations of LAES systems were analyzed in (Antonelli et al. 2017). The study proposed hybridizing the LAES with another energy storage technology of faster response time, such as Lithium-ion battery, to mitigate the intrinsically slow response of LAES. RTE in the range of 50 to 62% has been reported in the literature for LAES (Kim, Noh, and Chang 2018; Peng et al. 2018).

Batteries are the most ubiquitous electricity storage device due to their excellent modularity and scalability from fractional to Megawatt scale. Batteries have high energy density owing to the high energy levels that can be stored in chemical bonds. Megawatt-hour scale battery systems have emerged as a widespread option for grid-scale energy storage. Despite their ubiquity and high energy density, battery systems still face challenges. Batteries have relatively short lifespan and deep cycling them accelerates their deterioration (Luo et al. 2015). They require replacement every few years and they are made of hazardous chemicals. The process to dispose of them safely is environmentally and financially costly. A great deal of research and development effort has been invested in reducing the cost, increasing the lifetime and improving management systems of grid-scale battery systems (Chatzivasileiadi, Ampatzi, and Knight 2013; Mahlia et al. 2014; Luo et al. 2015). Lithium-ion batteries are so far the most mature and readily available for grid-scale storage. Current research is focused on better chemistries (Turney et al. 2014; Ning et al. 2015; Lu et al. 2015) for these batteries.

PSH is a mature technology with a relatively high RTE of 70 – 80% (Díaz-González et al. 2012). However, it is only economical at grid-scale of 100 MW and higher (Luo et al. 2015) and expansion of conventional PSH may be limited by geographical limitations. Energy stored in PSH depends on the total water mass pumped to the top reservoir and the elevation difference between the top and bottom reservoirs. The maximum possible energy capacity of PSH can only be increased by increasing the pumped water mass or increasing the elevation difference.

GLIDES was invented at the Oak Ridge National Laboratory (ORNL) and demonstrated for the first time in 2015) (Momen et al. 2016; Momen et al. 2019). It is a hybrid of PSH and CAES that has the potential to meet cost less than 100 USD/kWh (Abu-Heiba et al. 2018). GLIDES stores energy by compression and expansion of gas using a liquid piston inside high-pressure reservoirs. As shown in Figure 1, the GLIDES system consists of a high-pressure pump driven by electric motor, pressure vessels, a hydraulic prime mover, and an electrical generator. The pressure vessels are initially filled with gas under high pressure. During charging, the electric motor is run to drive the positive displacement hydraulic pump. The pump pushes liquid into the pressurized vessels. With the liquid volume increasing inside the high-pressure reservoirs, the gas above the water is compressed causing its pressure to increase. During discharging, the liquid is released from the vessels and the gas above the liquid column expands and its temperature decreases. If heat is available (e.g., waster heat) it could be used to counter the cooling effect of the gas expansion and augment power production. The liquid flows through the hydraulic prime mover (e.g., turbine) that drives an electric generator, and electricity is generated.

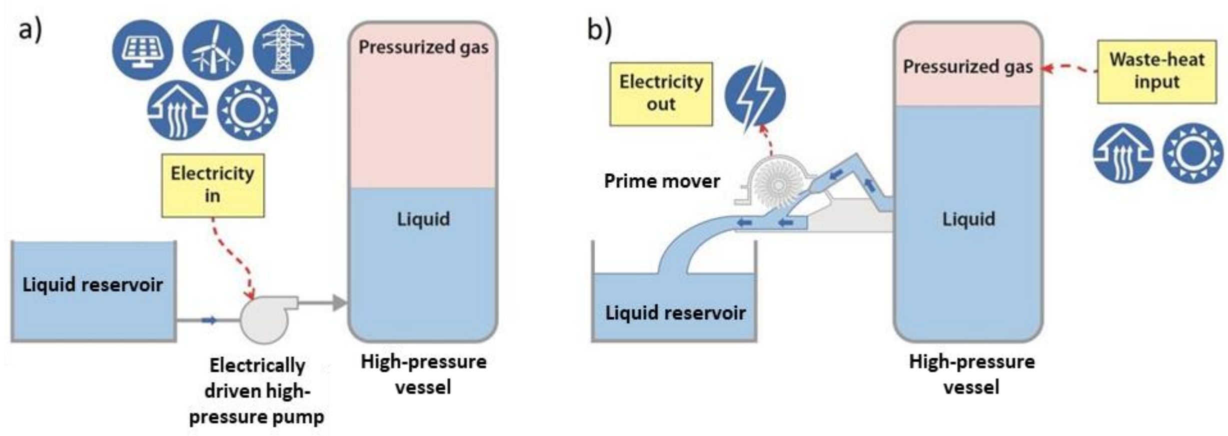

Figure 1. Layout of GLIDES during (a) charging and (b) discharging (Odukomaiya et al. 2016).

During the past 6 years, work has focused on improving the technoeconomic potential of GLIDES and identifying viable deployment applications. Improving the technoeconomic potential was accomplished through increasing the round-trip efficiency (RTE), increasing the energy density, and reducing the capital cost of the high-pressure storage containers. Several deployment applications were investigated including both behind- and in-front-of- the meter. The economics of integrating GLIDES to a hydropower plant was also investigated. This report presents the methodologies and findings of improving the technoeconomic potential and of investigating several deployment applications. Section 2.0 presents the different GLIDES configurations that have been developed thus far to increase energy density and RTE. Section 3.0 presents solutions to reducing the first cost of GLIDES. Section 4.0 presents technoeconomic analysis of building-level, community-level and wholesale-market use cases of GLIDES. Section 5.0 summarizes the conclusions of our findings and identifies the opportunities for future work and commercialization.

2.0 System Configurations[1]

Several GLIDES configurations have been developed aiming to increase the RTE and energy density. In 2015, the first GLIDES prototype was built, and therefore was given the designation "base configuration". Cost and experimental performance analysis were conducted, and areas of improvement were identified. Based on this knowledge, more efficient and more economical variations of the base configuration were developed. These were designated as "advanced configurations". The base and the advanced configurations used air for the gas to be compressed inside the high-pressure storage reservoir and water for the liquid to be pumped into the vessels. They depended on the compressibility of the air to store energy. Another configuration was developed that used different gas that changes phase during the charging and discharging processes. This configuration was designated "condensing GLIDES". In the remainder of this section, the configurations and relative improvements will be presented.

2.1 Base Configuration

A lab-scale base configuration was built and demonstrated at ORNL in 2015. A schematic of the base configuration prototype system is shown in Figure 2. The system was sized at a nominal storage capacity of 3 kWh and a maximum power output of 3 kW. This prototype used a custom-built Pelton turbine with two individually activated jets for better control of power output. A 500-gallon atmospheric tank was used as water storage reservoir. Air was compressed in four 500-liter carbon steel pressure vessels with rated maximum allowable working pressure of 160 bar. An 11-kW 42-liter/min positive displacement electrically driven pump was used to pump the water from the water storage tank into the high-pressure vessels. The Pelton turbine drove a 5-kW single phase 120 VAC 60 Hz electrical generator.

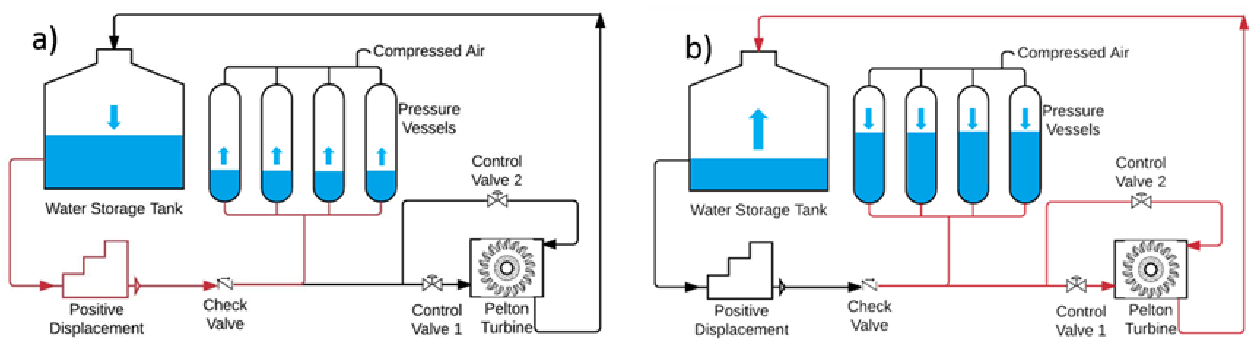

Figure 2. Schematic of the GLIDES base configuration during a) charging and b) discharging. The red lines indicate the active flow path. The arrows in the vessels and the storage tank indicate the direction of the level of the water (i.e., rising or falling level)

The system was designed to operate from minimum pressure of 70 bar to maximum of 138 bar. Figure 3 shows images of the prototype and components installed at ORNL.

[1] Content in this chapter (figures, text, and equations) adapted from: Kassaee, S., et al., (2021) Experimental and Simulation Analysis of a Near-Isothermal Spray-Cooled Air Compression in a Ground-Level Integrated Diverse Energy Storage Technology. Unpublished manuscript as of the date of writing this manuscript (June 2021), Oak Ridge National Laboratory, Oak Ridge, TN, US.

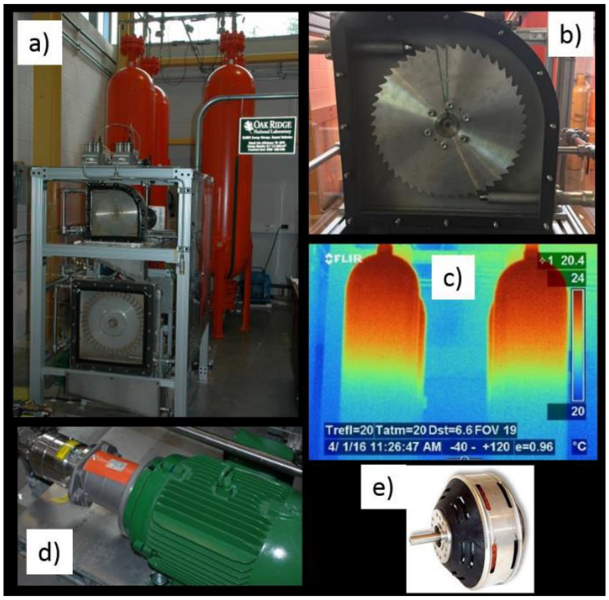

Figure 3. GLIDES base configuration prototype a) overall system and pressure vessels, b) Pelton turbine, c) IR image of pressure vessels during charging, d) charging pump/motor assembly, e) electric generator

The prototype was run, and the losses were characterized from the collected measurements as shown in Figure 4. The highest losses were incurred by the turbine, the pump and the motor. Elevated losses in the turbine and the pump were determined to be impacted by lack of component optimization for the working conditions. The RTE for the prototype was 22%.

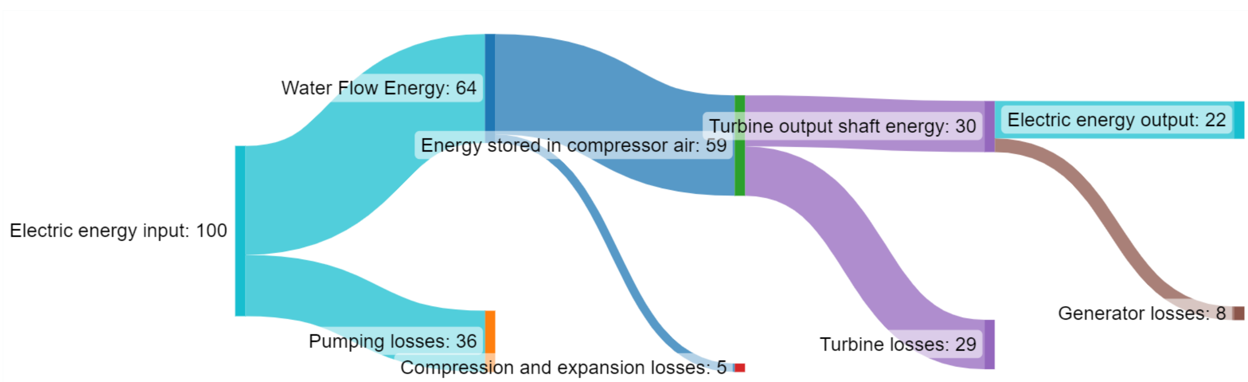

Figure 4. Sanky diagram of the energy flows in the base configuration (unit: %)

As shown in Figure 5a, the air temperature inside the pressure reservoir increases by around 45 °C during the charging process. When the charging process stops, the temperature of the air inside the pressure vessels decreases as the system exchanges heat with ambient. Given enough time, the temperature inside the pressure reservoir reaches ambient temperature. The decrease in temperature causes a decrease in pressure and hence loss of stored energy. During discharge, the temperature of the air decreases due to expansion causing the pressure to decrease even further than it would if the temperature remained constant. The energy loss due to these swings in air temperature and pressure can be shown as the area enclosed between the curves from 1 to 2 (compression process) and 3 to 4 (expansion process) on the Pressure vs Volume diagram shown in Figure 5b.

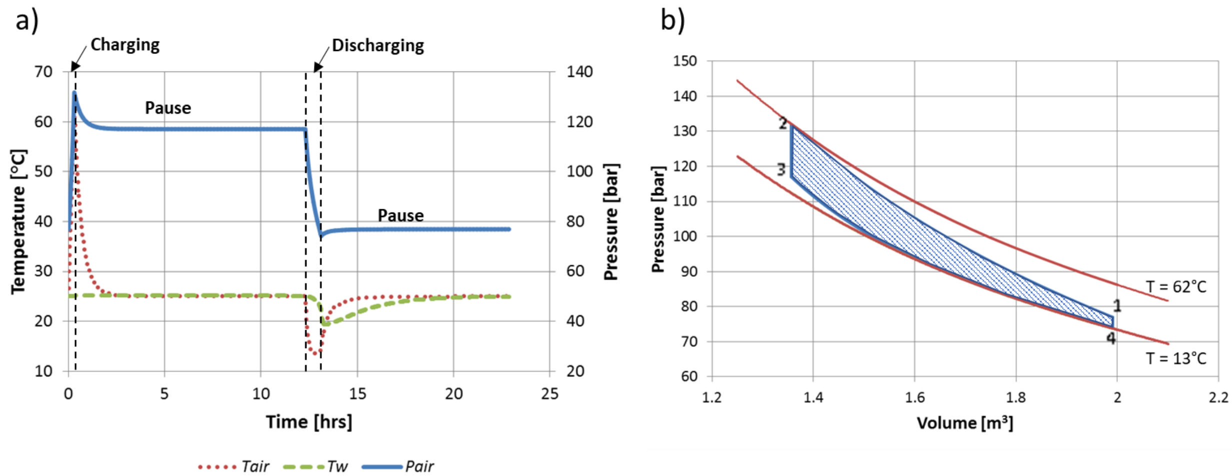

Figure 5. Performance of the GLIDES base configuration prototype a) Air and water temperature (*Tair and Tw*, left axis), and air pressure (*Pair*, right axis) during a complete charging and discharging cycle b) Volume-pressure diagram of the full-cycle.

The energy density and the electric-to-electric RTE of this configuration were calculated from the experimental data and determined to be 0.23 kWh/m^3 and 22%, respectively.

2.2 Advanced Configurations

To reduce the losses associated with the air temperature swings during compression and discharge, advanced configurations of the GLIDES system were introduced by (Odukomaiya et al. 2016). Figure 6 shows two advanced configurations next to the base configuration for comparison. In configuration 2 (Figure 6, b), water is pumped into the top of the vessel through spray nozzle. As the water is sprayed, micron size droplets directly exchange heat with the compressed air while traveling from the top of the vessel to the water level. The heat of compression is transferred to the water and the compression process takes place nearly isothermally. In configuration 3 (Figure 6, c), water is recirculated from the bottom of the vessel and sprayed into the top of the vessel during the discharge process. As the air expands and its temperature decreases, the sprayed water exchanges heat with the air and maintains its temperature nearly constant during the discharge process. If an external heat source is available (e.g., waste heat), it could be used to increase the temperature of the recirculated water during discharge. This increases the temperature and pressure of the air resulting in increase in power output of the system.

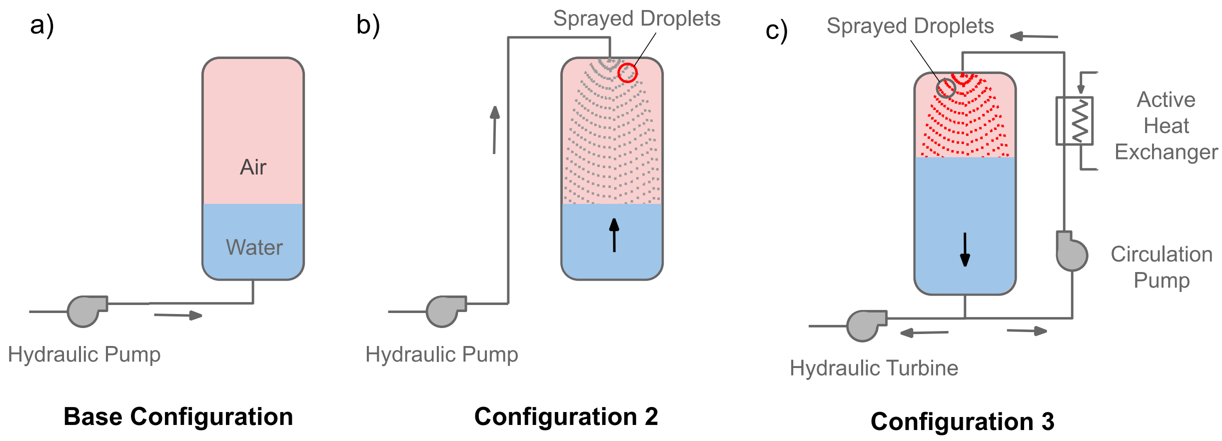

Figure 6. GLIDES a) Base, water is pumped into the vessel from the bottom b) Configuration 2, water is sprayed into the top of the vessel through spray nozzle to remove the heat of compression from the air, and c) Configuration 3, water is recirculated, and possibly heated, during discharge to counter the cooling effect of expansion

An advanced configuration prototype that combines configuration 2 and configuration 3 was built. The prototype used a 287- liter carbon fiber pressure vessel as the pressure reservoir, a reversible electric motor/generator which works as a motor during the charging process and as a generator during the discharge process, and a reversable hydraulic pump/motor which works as a pump during the charging process and as a hydraulic motor during the discharge process. A second pump was added to recirculate water during discharge, and a heater wrapped around the recirculation line to emulate waste heat. Photo of the prototype is shown in Figure 7.

Figure 7. Photo of the GLIDES advanced configuration prototype.

The vessel was filled with 18 kg of air at an initial pressure of 55 bar and initial temperature of 21.7℃. Charging was done at an average flow rate of 4.4 L/min and was terminated when the pressure of air reached 98 bars. To charge the system, water was pumped into the top of the vessel through the spray nozzle. During the compression process, as seen in Figure 8, the air temperature increases from 21.7℃ to a maximum temperature of 26.3℃. This only a 5.4 °C increase in air temperature compared to a 20 °C increase if water spray was not used, making this a near isothermal compression with a polytropic constant of 1.03.

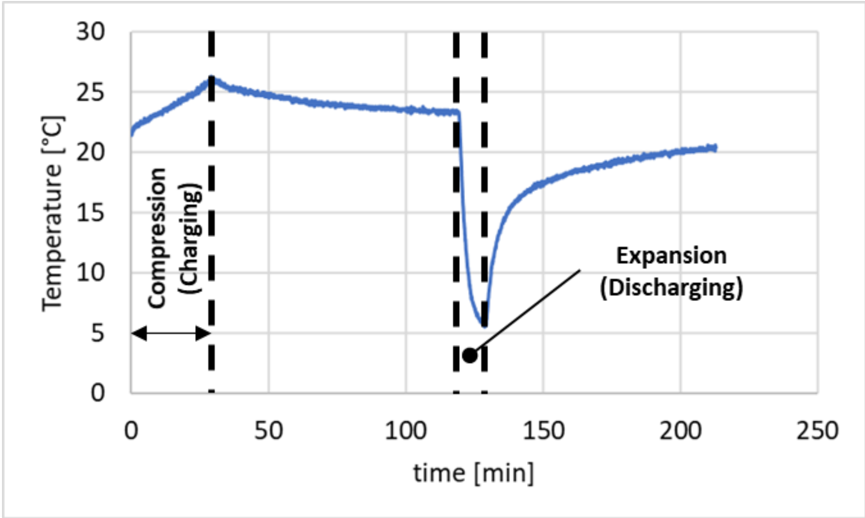

Figure 8. Temperature vs. time during a full charging and discharging cycle of the GLIDES advanced configuration (configuration 2) using spray charging. Spray was inactive during discharging.

The pressure time trend is shown in Figure 9. The drop in pressure following the charging process is significantly minimized. Over 90 minutes, the pressure dropped from 97.4 bar to 96.4 bar.

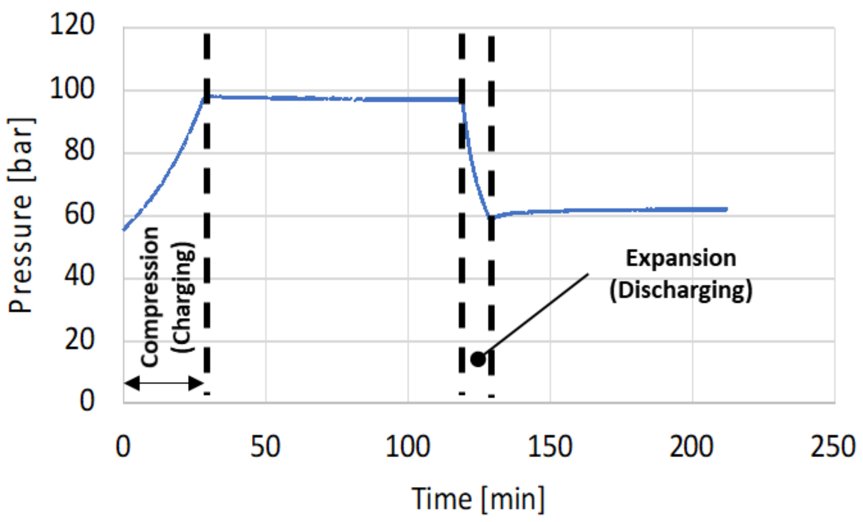

Figure 9. Pressure vs. time during a full charging and discharging cycle of the GLIDES advanced configuration (configuration 2) using spray charging. Spray was inactive during discharging.

The experimentally calculated energy density and RTE of this advanced configuration prototype were 0.781 kWh/m^3 and 51.6%, respectively. This was a 240% and 146% increase in energy density and RTE, respectively, relative to the base configuration. The simulation indicates that the configuration 2 can be further improved to reach RTE of 70% as shown in Figure 10 (Odukomaiya et al. 2016). These improvements were attributed to the use of more efficient pumping and generating components, and the use of spray charging. It is worth noting that recirculation during discharging (configuration 3) could not be performed experimentally due to issues with the recirculation pump. Table 1 provides a summary of technical characteristics of the various energy storage technologies

Table 1 Technical characteristics of the various energy storage technologies

Technology	RTE %	ED [kWh/m^3]	Capital Cost [$/kWh]	Lifetime [years]
PSH[1]	70-85	0.5-2	5-100	40-60
CAES[1]	42-53	2-6	2-120	20-40
Flywheel[1]	90-95	20-80	1000-5000	15+
Lead-acid[2,3]	63-90	50-100	120-600	5-15
Lithium-ion[2,4]	90-99	240-730	150-1300	5-15
Na-S[3]	75-90	150-300	250-500	10-15

1: Krishan et al, 2018; 2: Luo et al, 2015; 3: Hannan et al, 2017; 4: Ulvestad, 2018

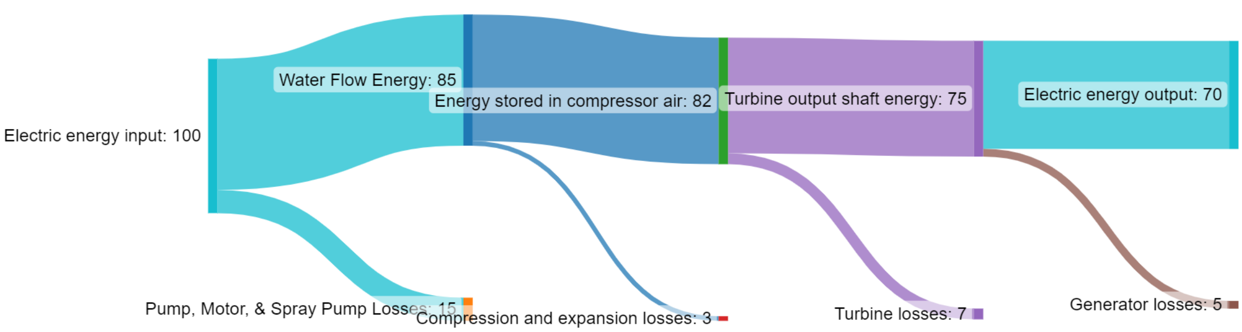

Figure 10. Sanky diagram of the simulated energy flows in the configuration 2 (unit %)

2.3 Condensing GLIDES

GLIDES originally employed water and air for the compression liquid and the compression gas, respectively. The energy stored in GLIDES is from compression work done by the rising water level in the vessel. Equation (1) shows the relationship between work, pressure, and the volume of the compression gas. To increase the energy stored indicated by W, only two parameters can be changed, pressure P and volume displacement (initial volume V_0, final volume position V_f).

$$W = -\int_{V_0}^{V_f} P\, dV\,, \qquad V_f < V_0 \tag{1}$$

Therefore, to store more energy in the same total vessel volume using air and water, maximum gas pressure must be increased. As each pressure vessel has a set maximum allowable pressure based on the material used and their strength, increasing this maximum pressure requires stronger vessels which results in higher vessel/GLIDES cost per kWh. To increase the volume displacement, a condensable gas is employed. As the density of the condensed fluid is higher than that of the vapor phase, higher liquid volume displacement would be achievable. Therefore more working fluid can be pumped into the vessel as shown in Figure 11. Detailed model and simulation study of the impact of using condensing fluid in GLIDES on its energy density is reported in (Abuheiba et al. 2020).

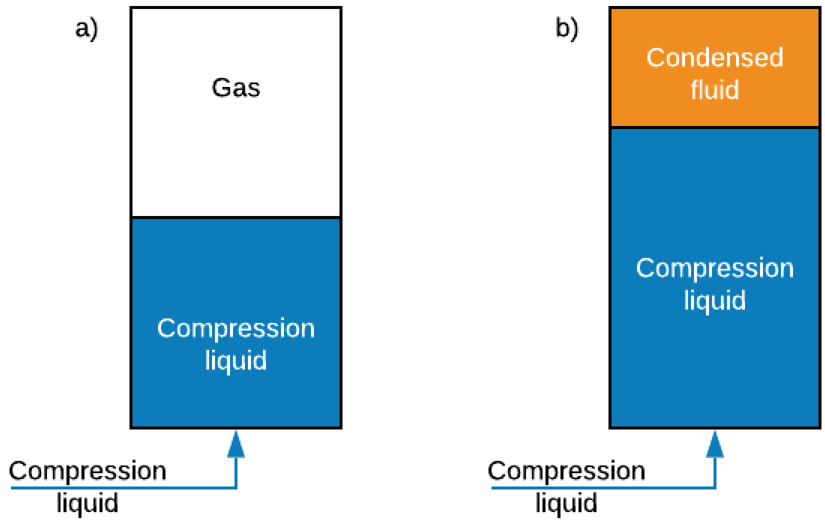

Figure 11. Within the same pressure limits, a non-condensable gas system (a) will utilize less volume than a system with condensable gas (b) (Abuheiba et al. 2020).

A proof-of-concept prototype of the condensing GLIDES configuration was built and evaluated in the laboratory. The prototype used Carbon Dioxide (CO_2) as the gas in the high-pressure vessel and mineral oil as the compression liquid as shown in Figure 12. CO_2 was chosen because of its non-toxicity, non-flammability and availability. It is also the pure fluid that has the highest condensation pressure at room temperature. Experimental measurements indicated energy density and RTE of 1.21 kWh/m^3 and 89%, respectively. This condensing GLIDES prototype used hand pump to push the compression liquid into the pressure vessel (tube) and did not use a generator due to the small scale of the prototype. Therefore, direct comparison to experimentally calculated energy density and RTE of the base and advanced configurations cannot be made. However, the use of a condensing working gas provides advantages beyond improvement in energy density and RTE. Most importantly, as phase change takes place at constant pressure, the off-design working pressure for pumping liquid and generating electricity falls within a narrow range. Pumps and turbines would therefore always operate at, or very close, to their optimal operating conditions.

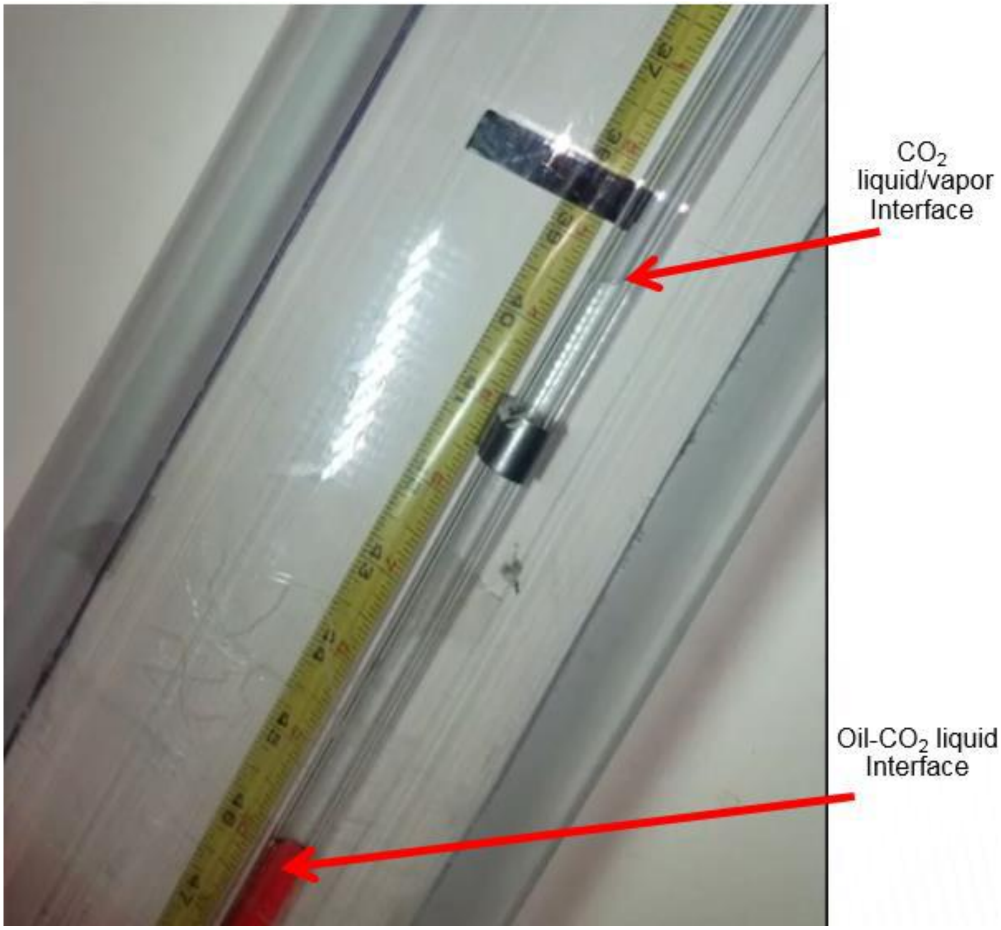

Figure 12. Photo of the condensing GLIDES prototype during CO_2 compression (charging) process. Length of CO_2 liquid column increases as more oil was pumped into the tube, causing more CO_2 to condense.

Despite the relatively high condensing pressure of CO_2, it still may be low if energy density is of high priority. To overcome this limitation, a hybrid variation of the base configuration and the condensing GLIDES configuration was investigated analytically (Abuheiba et al. 2020). In this proposed hybrid configuration, the gas being compressed is a mixture of air and CO_2.[1] The study concluded that at an optimal blend ratio of air and CO_2, the energy density could be increased by up to 40% over the base configuration.

[1] While CO_2 has a higher condensation pressure, air is included in the final gas mixture to help keep gas pressure within desired limits.

3.0 Options to Reduce Cost of Compressed Air Vessels

Based on cost analysis that was done while building the base configuration GLIDES prototype, more than 90% of the system first cost was associated with the cost of the pressure vessels. The base configuration prototype used carbon steel pressure vessels. Carbon steel vessels are designed and built on an as-needed basis. Their manufacturing is largely non-automated. Intensive manual labor and high welding costs are associated with the manufacturing of these vessels, causing them to be the highest cost item of GLIDES. To reduce the capital cost of GLIDES, carbon fiber pressure vessels and high-pressure pipe segments were investigated as alternatives to the carbon steel vessels (table 2). Carbon fiber vessels and high-pressure pipe segments are generally less expensive as they are mass manufactured, and their manufacturing is highly automated. However, they impact the first cost of the system in different ways. The maximum volume of mass produced carbon fiber vessels is relatively small (less than 300 liters) for GLIDES. Larger number of carbon fiber vessels may be required compared with carbon steel vessels for the same GLIDES capacity. Increase in the number of vessels increases the cost of piping, fittings, and instrumentation and control. When used as pressure vessels, pipe segments are capped, and flow ports are welded to their ends. Therefore, use of pipe segments may increase the capital cost due to increased welding and valving. To investigate the potential of reducing the first cost of GLIDES, a technoeconomic model was developed. The model combines cost and performance models to determine the pressure reservoir alternative that minimizes the first cost of GLIDES given its rated kW and kWh. The details of the cost analysis model were reported in (Kassaee et al. 2019) and the findings are presented in Section 3.1. In Section 3.2, other non-conventional alternatives to conventional pressure vessels are summarized.

Table 2. System cost breakdown of a 200 kWh system

Technology	Steel pressure vessels	Carbon fiber vessels	High-pressure pipe segments
Total, K$	1235	651	225
Pressure vessel, K$	1190	580	176
Turbine/generator, K$	33	33	33
Motor/pump, K$	8	15	8
Fitting, K$	4	23	8
RTE, %	83	74	76
Energy density, kWh/m^3	0.51	2.45	1.42

3.1 Cost Analysis

The first cost of a GLIDES system of the base configuration was calculated for rated power of 0.1, 1 and 10 MW system for storage duration of 4 and 6 hours. The range of rated power was chosen to cover the range of small to grid-scale energy storage. The range of storage duration is what is generally acceptable for daily storage. For each combination of rated power and storage duration the cost model determines the optimal initial pressure, pressure ratio and total storage volume to minimize the capital hardware cost. The model then calculates the cost of GLIDES if carbon steel vessels, carbon fiber vessels or pipe segments were used, then outputs the minimum cost. Pipe segments were the lowest-cost option for all sizes. The capital hardware cost of pipe-segment GLIDES is shown in Figure 13 for different system sizes. The capital hardware cost can be as low as ~350 $/kWh for 10-MW/6-hour system with ranging from $250/kWh for a 300 MW and 6 hours system to $1,100/kWh for a 10 kW and 2 hours system.

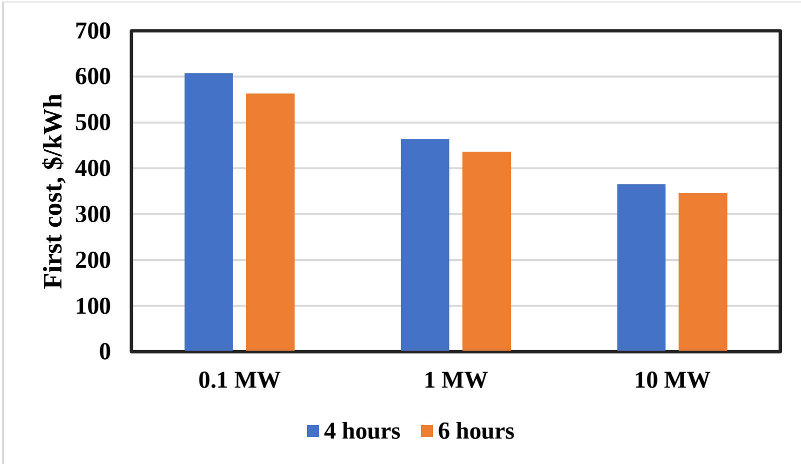

Figure 13. Capital cost of hardware of different sizes of GLIDES system using pipe segments for the high-pressure gas container.

3.2 Non-conventional Alternatives to Vessels

As explained in the Results section, most of the cost associated with the GLIDES system is attributed to the pressure vessels. Other promising alternative pressure reservoirs were investigated. In section 3.1, commercially available carbon fiber vessels and pipe segments were investigated as pressure reservoirs alternatives to carbon steel pressure vessels. Other alternatives are explored in this section. These alternatives are either naturally occurring (underground reservoirs) or already existing assets (abandoned pipelines). These alternatives are designated "non-conventional". Despite their low capital cost advantage, they limit the deployment location to where they are physically located.

Underground reservoirs have been used for natural gas storage for decades (FERC 2004). Besides lowering the GLIDES capital cost, smaller footprint and larger storage volumes are advantages of using underground reservoirs for GLIDES. Underground reservoirs are categorized into depleted oil/gas reservoirs, aquifers and caverns. As the productivity of a well decreases or the well operation is not economical anymore, the operator is required to remove all equipment and seal the abandoned well to prevent leakage. Some wells are plugged, meaning all equipment was removed and the top and bottom of the well was filled with cement as required. In many cases, however, wells are not plugged and are abandoned. This mostly happens when oil prices drop and the operator files for bankruptcy. In some cases some wells are abandoned without being sealed, especially for wells drilled in early 1980s. Depleted oil and gas reservoirs are the most common underground natural gas storage facilities (EPRI and Energy. 2003). These reservoirs occur naturally, but as they are not originally designed to be leak tight, a pressure test is required to determine the maximum pressure the reservoir can practically hold (FERC 2004). Around 2.3 million abandoned wells exist in the United States (Fall et al. 2011; Raza et al. 2017). It should be mentioned that most of the depleted fields that were converted to gas storage reservoirs are from depleted gas fields and not oil fields, as the combination of oil, gas, and water causes issues (Kruck et al. 2013). Typically, owners and operators of the storage sites of natural gas are the interstate pipeline companies, distribution companies, and independent companies. The cost associated with using oil and gas reservoirs for storing natural gas is reported between $5 million and $6 million per billion ft^3 (between $177 and $212 million per billion m^3) (FERC 2004). Cost analysis of a GLIDES system using 1 billion ft^3 underground reservoir was performed. Assuming a maximum pressure range of 10–100 bar and machinery (pump, turbine and piping) cost of $1 million, a $/kWh cost of $13.6/kWh to $136.91/kWh can be achieved, respectively (Kassaee et al. 2019).

Aquifers are naturally occurring porous and permeable rock formations which contain freshwater or brine in the pore spaces. Aquifers are typically sandstones or carbonate rocks. Therefore, cap rocks are required to make them suitable for storage. Multiple wells can be drilled, depending on geographical conditions, which can give the option of pumping water from two wells into the reservoir and displacing air in another well. Aquifers are known to be capable of storing large volumes of gas. Using this storage volume, water/brine can be pumped down the well to compress existing/compressed air inside the reservoir. The air pressure in the reservoir is known to be equal to that of the local water pressure at static conditions when used for CAES. The pressure response of the aquifer is dependent on the permeability of the rock and the viscosity of the fluid, which affects how fast the liquid can flow in the reservoir. The main disadvantage with this system is that for them to be utilized for GLIDES the flow rate of the compression liquid into the aquifer would have to be low. This causes this storage type to be only used one annual cycle at steady injection/withdrawal rates. Minimum and maximum mean storage pressures of 20 and 80 bars are recommended (FERC 2004; Kushnir, Ullmann, and Dayan 2012; Kruck et al. 2013). A number of aquifers have operated as natural gas storage reservoirs for many decades (Kassaee et al. 2019).

Salt caverns are another potential underground storage reservoir. Over the decades, with the oceans and lakes evaporating, the resultant leftover salt is buried underneath layers of dust. Solution mining is used to extract salt from the salt domes or salt beds, which can be as deep as 2 km beneath the surface. Solution mining is done by drilling a well into the salt formation and dissolving the salt by injecting water. As the salt is dissolved in water, the brine is displaced to the earth’s surface, creating a large empty space. A blanket medium is injected which has a lower density than both water and brine, keeping the salt in the upper part of the cavern from dissolving in the water to prevent the cavern from collapsing. Leaching can be continued until the planned cavern size is reached; it is recommended not to exceed a height-to-diameter ratio of 5.0 (Kushnir, Ullmann, and Dayan 2012; Kruck et al. 2013). Cavern sealing is not required in solution mined salt caverns due to their low permeability and self-healing characteristics (Kushnir, Ullmann, and Dayan 2012). The cavern construction process can take up to 5 years depending on the desired cavern size (multiple caverns can be mined close to one another to increase the storage volume if desired). As the cavern construction period can be long and the cost expensive, other options can be considered, such as working with salt companies with extensive experience in solution mining or using existing salt caverns. Also, some profit can be made by providing the brine from mining to the salt/chemical companies.

A challenge to using salt caverns as pressure reservoir for GLIDES are the solubility of salt in water if water is used as the compression liquid in GLIDES.. The cost associated with operating salt caverns as pressure reservoirs can go upwards of \$10 million/Bcf (\$353 million/Bm^3). There are two working CAES plants in the world that use salt caverns as pressure reservoirs—one in Huntorf, Germany, and one in the United States in Alabama. The CAES plant in Germany uses two salt caverns and provide 321 MW over a 2-hour period and has a total volume of around 310,000 m^3 with a 43 bar regular minimum operational pressure and a 79 bar allowable maximum working pressure. The Alabama plant can provide 100 MW over a 24 hour period and has one salt cavern with a volume of around 540,000 m^3 designed to operate between a minimum pressure of 45 bar and a maximum pressure of around 74 bars (Kushnir, Ullmann, and Dayan 2012; Kruck et al. 2013; Institute 2018). Other mining options include hard-rock mining techniques, which can be used to create hard-rock caverns. Hard-rock mining techniques include tunnel boring machine, drilling, and blasting. These caverns can be located at any depth desired with almost any desired shape, but as expected, rock strength improves with depth. Structural strength, low permeability, and adequate volume are required of each selected location. Sealing is most likely needed to prevent leakage in this technique (Kushnir, Ullmann, and Dayan 2012). Hard-rock caverns are expensive, and therefore small scale would be more desirable (Kassaee et al. 2019).

So far, the explored non-conventional underground pressure reservoir options are naturally occurring. A non-naturally occurring option is pipeline. A pipeline is said to be abandoned when its owner is no longer in need of the pipeline and is either intending to remove the pipes or leave them in place. Regardless of the owner's decision, the owner is required to clean the pipes and if the pipes are to be left in place, the ends must be locked to prevent damage to the environment. As this task is costly for the owners, reusing them as storage vessels can eliminate the need of the owners having to cover this cost. These pipes are rated for high pressures, usually up to 1500 psi, and could be adopted for use as pressure reservoirs for a GLIDES system. The major cost associated with these pipes mainly involves welding activities.

4.0 Use cases

Four uses cases were developed and their technoeconomics were analyzed to demonstrate the economics of potential applications of GLIDES. The use cases considered were selected for small scale (10s kW), medium scale (100s kW) and large scale (1000s kW) GLIDES applications. In the small-scale use case, arbitrage and load shifting were the only revenue streams. In the medium-scale use case, load shifting and energy capacity were the only revenue streams. In the large-scale use cases, grid and ancillary services were the only revenue streams. In the following 3 subsections, the use cases and their results are presented.

4.1 Local Energy Market – Small Scale GLIDES

Rising electricity generation from renewable sources and the associated rise in storage technologies have attracted attention to the potential of demand side management to replace the traditional generation-dominant operation of the power grid. Within that context, buildings are changing from a consumer to a two-way prosumer (producer & consumer). For instance, several studies have presented frameworks to quantify demand response potential of aggregated residential and commercial buildings (Gkatzikis, Koutsopoulos, and Member 2013; Tang et al. 2018). Many pricing strategies for utility companies have been proposed to better leverage response potential using a Stackelberg game (Yang, Tang, and Nehorai 2013) and data-driven approaches (Xu et al. 2018). Besides efforts to incentivize the demand side to participate in market services at the transmission or distribution levels, local energy transactions at the community level (Bremdal et al. 2017) are also being motivated by decentralized local renewable generation which has the advantage of significantly reducing the power loss in distribution networks. The prosumer-building ecosystem presents an opportunity for GLIDES to provide value for prosumers through arbitrage and load shifting. Within that ecosystem, aggregating multiple prosumers is a major advantage to both the owner of the energy storage and to the prosumers. A large locally centralized energy storage reduces cost to prosumers and improves economics of the energy storage system.

Given its potential, we chose to study the use case of GLIDES as a locally centralized energy storage system to multiple prosumer buildings. The goal of the study was to assess the value proposition of GLIDES in such a local market. Figure 14 shows the arrangement of the studied local market use case. Three buildings equipped with PV panels bi-directionally trade power with the local market operator. Each building has different load profile. The local market operator operates and owns GLIDES and, in addition to bi-directionally trading energy with the prosumers, it bi-directionally trades power with the electric grid. In the upper level (GLIDES-Grid), the purchasing and selling price of electricity is set by the grid operator. In the lower level (GLIDES-prosumers), the purchasing and selling price of electricity is set by the local market operator. When the upper level electricity price is lower, GLIDES is charged and when it is higher, GLIDES sells electricity to the lower level building prosumers at a better price (less than external price). Therefore, the local market operator benefits from the price arbitrage and the lower level prosumers benefit from better electricity pricing (local electricity selling price is higher than external selling price and local electricity purchasing price is lower than external purchasing price). Building prosumer could also shift their load profile to further reduce operation cost based on the local trading price. Load shifting cost factor is used to represent the inconvenience cost of load shifting: the higher the cost factor is, the higher the inconvenience cost will be.

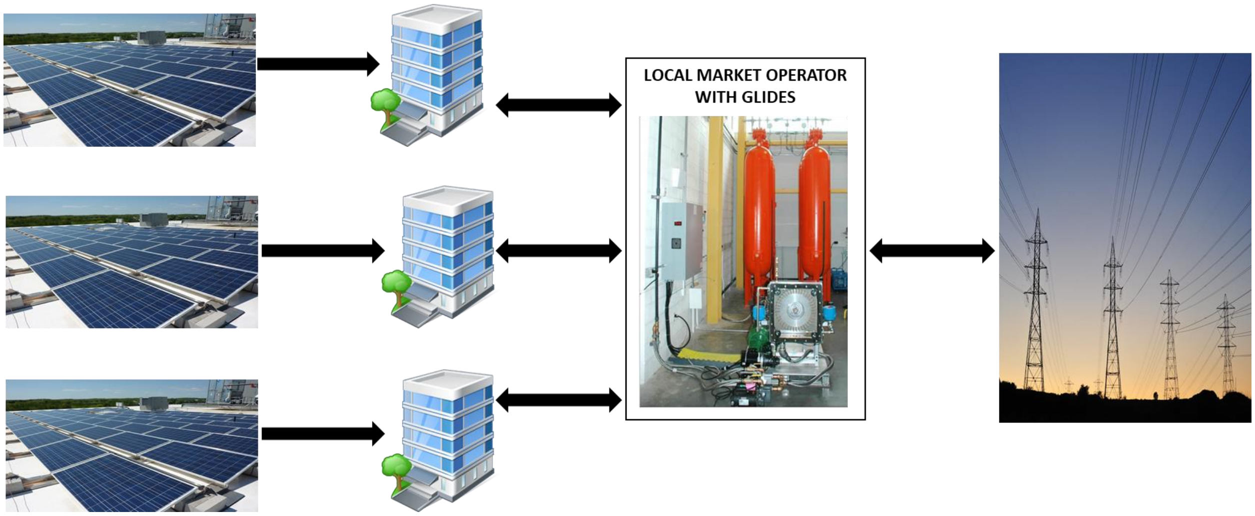

Figure 14. Arrangement of the studied local market use case. GLIDES operator bi-directionally trades power with both the prosumers (buildings with PV generation) and with the electric grid. The black arrows indicate the direction of electric power flow.

The study optimized the trade at the lower level (prosumer-operator) and at the upper level (operator-grid) to maximize revenues for both the operator and the prosumer. Cost factor was assigned to the load shifting of the prosumers and was changed parametrically. The optimization considered two cases: 1) local purchasing price equals local selling price, and 2) local purchasing price is greater than local selling price. The detail of the model and the simulation are reported in (Chen et al. 2020). The optimization was performed for one day and assuming GLIDES capacity of 20 kW/4 hours. GLIDES parameters in Table 3 were used in this study.

Table 3. GLIDES operational and economic parameters inputs to the local market use case

Parameter	Value
Capital cost, $/kW	700
Maintenance cost, $/kW/yr	0
Pump efficiency, %	90
Turbine efficiency, %	90
Minimum working pressure, bar	70
Maximum working pressure, bar	130

Table 4 summarizes each prosumer's operating cost and GLIDES profit for different load shifting cost factors and different trade pricing strategies. Note that, detailed operation model for GLIDES used in local energy transaction can be refer to study (Chen et al. 2020). In this case, GLIDES is modelled as local transaction center agent for one day operation. The profit of GLIDES in Table 4 is the operation profit in local energy transaction with three assumed building prosumers, the profit doesn't take capital cost into account.

Table 4. Cost comparison without & with local energy trading

Without local energy trading		
	Profit ($)	**Energy Cost ($)**

Load shifting cost factor	GLIDES	Prosumer 1	Prosumer 2	Prosumer 3
0.001	0	191.621	173.417	129.127
0.005	0	197.835	181.052	136.526
0.01	0	198.595	181.997	138.288
With local energy trading and local purchasing price equals local selling price				
	Profit ($)	**Energy Cost ($)**		
Load shifting cost factor	GLIDES	Prosumer 1	Prosumer 2	Prosumer 3
0.001	2.237	183.466	166.532	94.222
0.005	3.072	185.361	171.337	107.426
0.01	3.282	184.113	170.892	112.371
With local energy trading and local purchasing price is greater than local selling price				
	Profit ($)	**Energy Cost ($)**		
Load shifting cost factor	GLIDES	Prosumer 1	Prosumer 2	Prosumer 3
0.001	37.767	191.357	172.492	128.899
0.005	45.055	197.503	180.172	134.212
0.01	46.405	198.267	181.267	135.724

The results show that can provide value for both the prosumers and the operator. In the case of equal local purchasing and selling price, the operator makes a profit, although small. All prosumers save on energy cost. In the case of local purchasing price greater than local selling price, the operator makes much higher profit while the prosumers do not. It should be noted that these results are based on only time-of-use energy charge. If demand charge is included, profits will be much higher for both the operators and the prosumers.

4.2 PV-Powered Charging Station – Medium Scale GLIDES

The rise of electric vehicles (EV) presents a large and imminent opportunity for GLIDES. The transition to EV is well underway. As of 2020, 1.8 million battery and plug-in hybrid EVs were registered in the US (IEA 2021). The share of EV is expected to grow steadily in the coming decade to meet climate and sustainable development targets. EV sales in the US are forecast to range from 1.4 to 2.3 million in 2025 and 2.9 to 8.1 million in 2030. The Edison Electric Institute and the Institute for Electric Innovation have developed a consensus forecast of EV sales projections from 2018 to 2030 and have estimated the associated charging infrastructure needs (Cooper and Schefter 2018). It is projected that the number of EVs on the road will reach 18.7 million in 2030 and 9.6 million charge ports will be required. Also, the next 1 million EVs will be manufactured in less than 3 years (i.e., by early 2021). This growth in EVs is expected to add significant electrical demand nationally. Given the growth of EV charging stations and the use of renewable energy to power them, we chose to investigate this use case to compare the economics of GLIDES to batteries, the incumbent storage technology at this scale. Figure 15 shows the set up that was considered for this use case. A charging station with several charging slots is powered by the electric grid and PV. Energy storage is added to maximize the utilization of the PV.

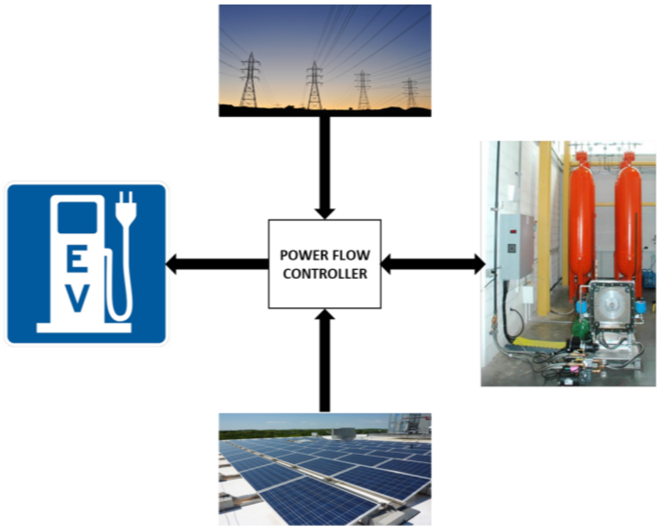

Figure 15. Set up of the use case. Charging station is powered by either the grid and/or PV. GLIDES is shown in this figure as the energy storage system, but the use case was investigated using batteries as well.

The goal of this study was to create surrogate model that can be used to estimate annual cash flow for any given PV size, storage capacity, EV arrival rate, and number of charging slots in a range based on limited number of samples. To better sample the parameters combination with good coverage in the range, Latin Hypercube Sampling method (LHS) is adopted. LHS is a statistical method for generating a near-random sample of parameter values from a multidimensional distribution. Two thousand combinations of these parameters were sampled using the LHS. The ranges of these four parameters are given in Table 5.

Table 5. Ranges of the parametric variables of the PV powered charging station use case.

Parameter	Studies range
Area of PV, m^2	200 – 1000
Storage rated power, kW	100 – 800
Storage duration, h	4
Number of charging slots	5 – 25
EV daily average arrival, EV/day	0 – 150

In this use case, the proposed co-optimization model is developed to balance (minimize) initial capital investment costs and future operational cost. One year operation is considered. The design space for charging station is four dimensional for this use case: number of charging slots, area of PV, energy storage, daily mean EV arrival number. So, for each combination of the parametersin Table 5, the dispatch of the storage system was optimized to maximize profit. Cost and operational inputs to all combinations are listed in Table 4. The details of the model and the simulation are reported in (Chen, Kassaee, et al. 2019).

Table 6. Economic and operational input data to calculate the annual cash flow of the PV powered charging station use case

Parameter	Value
Battery system capital cost, $/kW	1533

Battery maintenance cost, $/kW/yr	20
Battery min. and max. SOC, %	5 – 100
Battery RTE, %	95
GLIDES capital cost, $/kW	700
GLIDES maintenance cost, $/kW/yr	0
GLIDES min. and max. SOC, %	0 – 100
GLIDES pump efficiency, %	90
GLIDES turbine efficiency, %	90

The results of the 2000 sample points were used to train a "surrogate model". The surrogate model is simply a mathematical model that was trained to correlate the annual cash flow to the PV size, storage capacity and number of charging slots. Training of the surrogate model refers to systematically adjusting the parameters of the surrogate model so that the model outputs the training output given the training inputs. The trained model can then be used to predict the output of any combination of inputs within the ranges of the training parameters. In doing so, simple to use mathematical model is used in place of complex physics-based model. Example of the surrogate model output is shown in Figure 16.

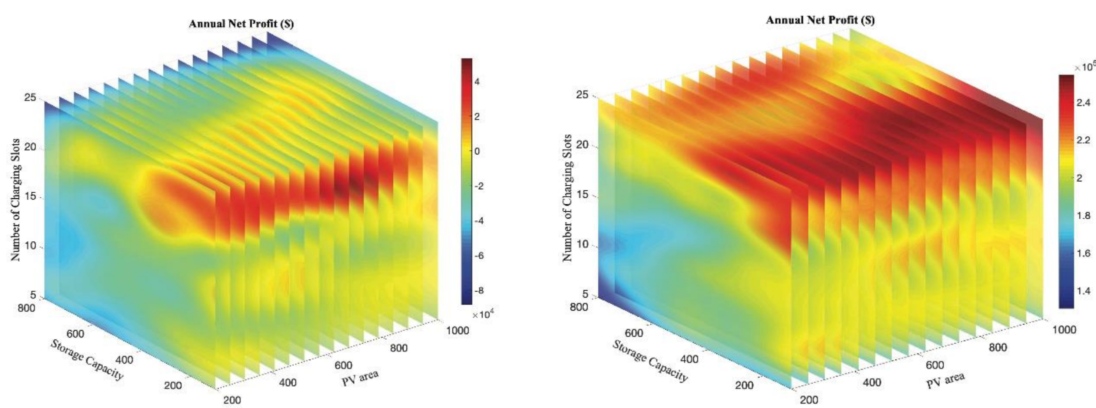

Figure 16. Annual cash flow calculated by the surrogate model using GLIDES as the storage system. Left is for arrival rate of 5 EV/day, right if for arrival rate of 55 EV/day.

The developed surrogate model can be used to find the optimal capacity of EV charging stations for any combinations of the input parameters in Table 5 and for the cost and operational parameters listed in Table 6. For this use case, it was found that GLIDES is more economical than batteries when the required power capacity is higher than 200 kW. Note that, since GLIDES is a mechanical type energy storage, its maintenance cost is generally low (mainly comes from the machine degradation) and doesn't depends greatly on its kW level. Here, the maintenance cost of GLIDES is set to be 0 as the best-case scenario. It can be used as base reference case.

4.3 GLIDES in a Hydropower Plant

The United States has large hydropower generation with a total installed 2020 capacity of almost 103,000 GW, which comprises about 80 GW of conventional hydropower and almost 23 GW of PSH (EIA 2021). This represents 9% of the total electricity generation capacity of the US. Hydropower accounted for 6.7%

of total electricity generation and 38% of electricity from renewables . Conventional hydropower plants are either of the impoundment or the diversion type. In the impoundment type, a dam is used to store river water in a reservoir. Water is released on demand and flows through a turbine driving an electricity generator. In the diversion type, portion of a river is channeled through a canal or penstock to flow through a turbine driving an electricity generator. Diversion type hydropower plants are sometimes called run-of-river (RoR). Unlike impoundment type plants, run-of-river (RoR) plants usually generate much less power (micro: <100 kW, mini: 100 kW-1 MW, small: 1-10 MW) because they cannot store water in large reservoirs. For the same reason, it is considered more environmentally friendly with less ecosystem disruption. Run-of-river hydropower plants have two main disadvantages:

a) Water limitation. RoR plants are limited by the river flow and seasonal variations in the flow. Forced outages might occur when reservoir level or water flow is too low.

b) Grid services. Run-of-river hydropower plants are not capable of participating in the high-profit ancillary grid service market because they cannot change their water flow to provide inertia to the power grid. Their revenue stream is limited to the low-profit energy market (Luo et al. 2018).

Given the above disadvantages, the potential of GLIDES in RoR hydropower plants is evident. GLIDES can simultaneously serve as both water storage and energy storage. Therefore, it can enable RoR hydropower plants to overcome both the water and the grid services limitations and provide them with more revenue streams. In this use case the integration of GLIDES into RoR hydropower plant is considered. Schematic of the proposed GLIDES-hydropower plant integration is illustrated in Figure 17. Physically, there are three main energy components: hydro turbine/generator, step-up transformer, GLIDES storage.

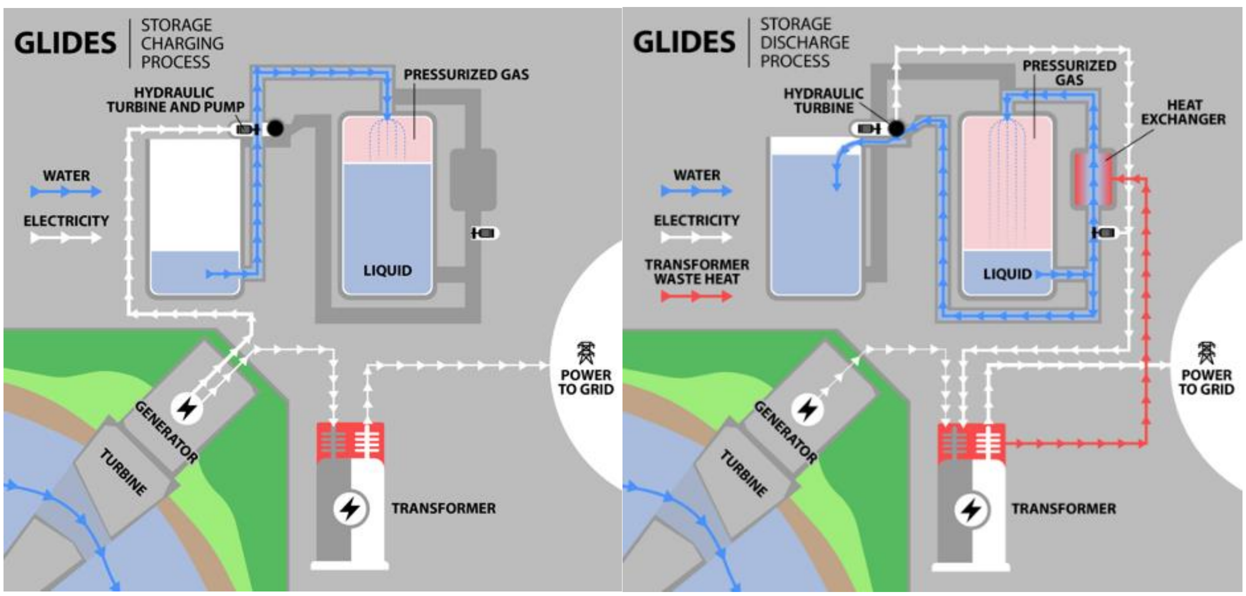

Figure 17. System schematic illustration and energy flow for integration of GLIDES with a hydropower facility

To evaluate the potential revenue of integrating GLIDES with a RoR plant, an Idaho Falls hydropower system on the Snake River was chosen as the reference site for simulating and economically analyzing the proposed integration. The system consists of 4 cascaded RoR hydropower plants: Lower Plant, City Plant,Upper Plant and Gem State Plant (see Figure 18 left). As water passes through each plant, electricity is generated. A water management agent was developed to simulate and provide water flow information for potential energy generation. Water flow data was taken from the United States Geological Service (USGS) stream gauge (name: Snake River NR Shelley ID site, site number: 13060000) located roughly 5 miles downstream from the Lower power plant and it measures 15-minute water flowrates and stores the information in USGS database (USGS 2021). Because the four cascaded plants are located in close proximity to each other, travel time of water between plants within the cascade is negligible and each of the four RoR hydropower plants has very limited operational control feasibility. For instance, the daily flowrate since April 2019 to March 2020 date is shown in Figure 19. The power generation data of the facility is also reported by utility to the U.S. Energy Information Administration. With the availability of power generation and water flow data, regression analysis can provide function that relates flow to power generation.

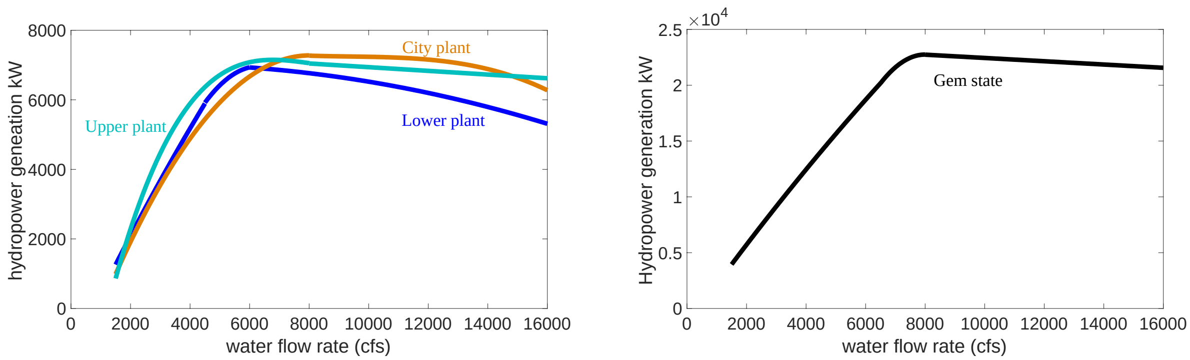

Figure 18. Left, power generation vs water flow rate for Upper, City and Lower power plant. Right, power generation vs water flow rate for Gem state power plant

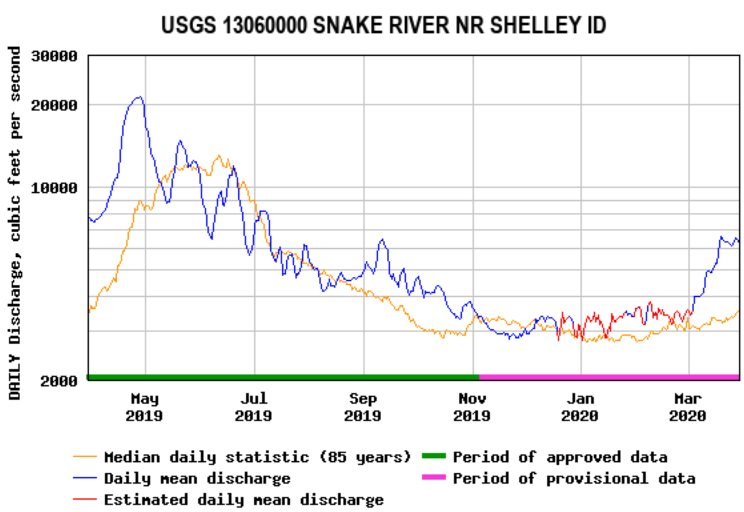

Figure 19. Daily discharged water flowrate measured at gauge site ID 13060000.

A model was developed to optimize the operation of GLIDES to maximize the plant revenue. Generation from the RoR plant could be used to charge GLIDES or sold to energy market directly. GLIDES could then sell energy at higher price to arbitrage in energy market, or it could bid its charging/discharging capacity into reserve and regulation market to provide contingency services. A GLIDES system of 1 MW power capacity GLIDES and 4 hours of storage capacity was simulated in the developed model. For hydropower generation, a representative week for each month was selected for simulation based on intra-weekly flow variability and average weekly flow rate criteria, see Table 7.

Table 7. Flowrate characteristics for each selected month.

Synthetic Month	Average Flowrate (ft^3/s)	Year Selected	Year Selected Avg. Flowrate (ft^3/s)	Days Selected for the Representative Week	Selected Week's Avg. Flow Rate (ft^3/s)
January	3,350	2006	2,917	4^{th} - 10^{th}	2,954
February	3,605	2015	3,546	7^{th} - 13^{th}	3,624
March	4,511	2011	4,440	21^{st} - 27^{th}	4,314
April	7,391	2000	8,481	3^{rd} - 9^{th}	7,123
May	12,156	2015	10,668	11^{th} - 17^{th}	11,053
June	12,827	2008	11,303	8^{th} - 14^{th}	11,054
July	7,471	2010	6,342	5^{th} – 11^{th}	6,400
August	4,978	1996	4,895	11^{th} -17^{th}	4,686
September	3,924	2004	4,306	22^{nd} – 28^{th}	4,317
October	3,233	1990	3,220	14^{th} – 20^{th}	3,154
November	3,499	2012	3,236	12^{th} – 18^{th}	3,227
December	3,488	2006	3,765	20^{th} – 26^{th}	3,751

The optimization model was run using a 5-minute timestep. For each of the selected 12 weeks, each day was then independently simulated. The results of the seven days were used to represent a typical weekly operation and associated energy and ancillary service transactions during a month. Typical weekly results were then used to forecast an annual net revenue for the RoR plant during a generic year. Net revenues were scaled by first computing the average daily revenues from 84 simulations (7 days per week time 12 months per year) multiplied by 365 days per year. The 5-minute hydropower generation profile for the 4 cascaded RoR plant in each selected month (data point: 84 days × 288 timesteps) are listed in Appendix 7.1.

Three different price profiles A, B, C are adopted from (Mahalik et al. 2019) and shown in Figure 20, Figure 21 and Figure 22 and are listed in Appendix 7.2. As explained in (Mahalik et al. 2019), these representative price signals are determined by discretizing historic total locational marginal price (LMP) into individual months, and then for each week. Normalized variability is defined as the indicator to reflect how much price changes within a timestep.

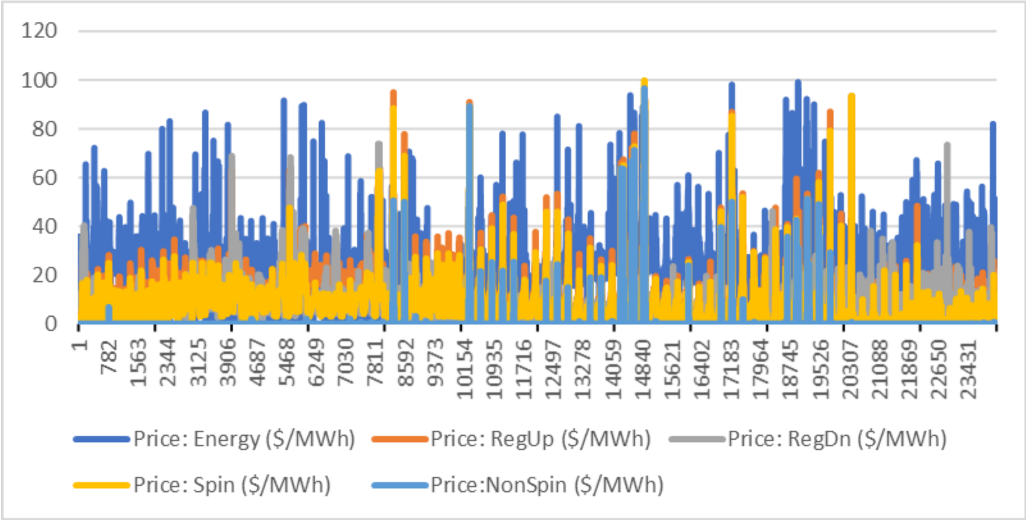

Figure 20. Different price signals in price profile A

The selected three price profiles could represent a range of prices and variability for the research. Profile A has a relatively high average total LMP and a relatively low normalized variability, the second profile B has an average total LMP and normalized variability reflective of the average of the dataset, and the third profile C has a relatively low average total LMP and a relatively high normalized variability.

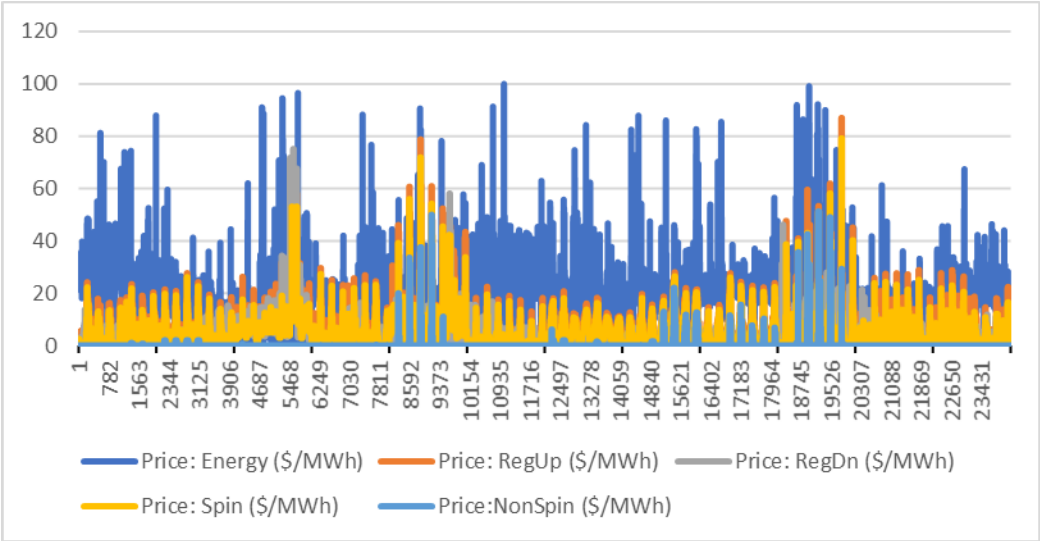

Figure 21. Different price signals in price profile B

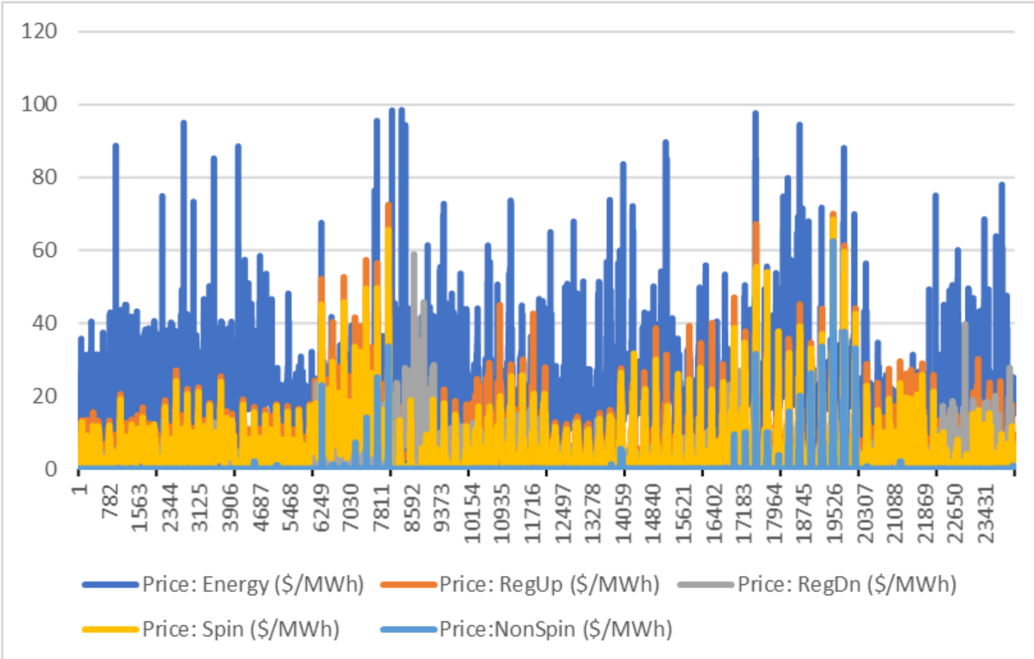

Figure 22. Different price signals in price profile C

The detailed average prices for LMP, operating reserves, regulation services of the three price profiles are summarized and compared in Table 8.

Table 8. Average prices and total variability for three representative price profiles .

Price Profile	Reserve ($/MWh)		Regulation ($/MWh)		Locational Marginal Price ($/MWh)	Total Normalized variability
	Up/down spinning	Non-spinning	Up	down		
A	10.15	3.20	13.96	7.85	24.19	159.26
B	5.48	0.50	8.07	4.64	21.80	305.90
C	5.57	0.62	10.15	6.95	20.65	497.81

Figure 23 summarizes the forecast total annual energy exported to the grid by the four RoR plants together with and without GLIDES for each price profile. Without GLIDES, the amount of energy generated by the four plants is the same regardless of the price profile. When GLIDES is integrated with the RoR plants, the total energy provided to grid by the integrated hydropower plant-storage system (IHSS) is lower. For example, with price profile A, 269,218 MWh energy is provided by IHSS which is less than the 272,281 MWh that was provided by hydro-only system. This is due to roundtrip energy loss associated with charging and discharging GLIDES.

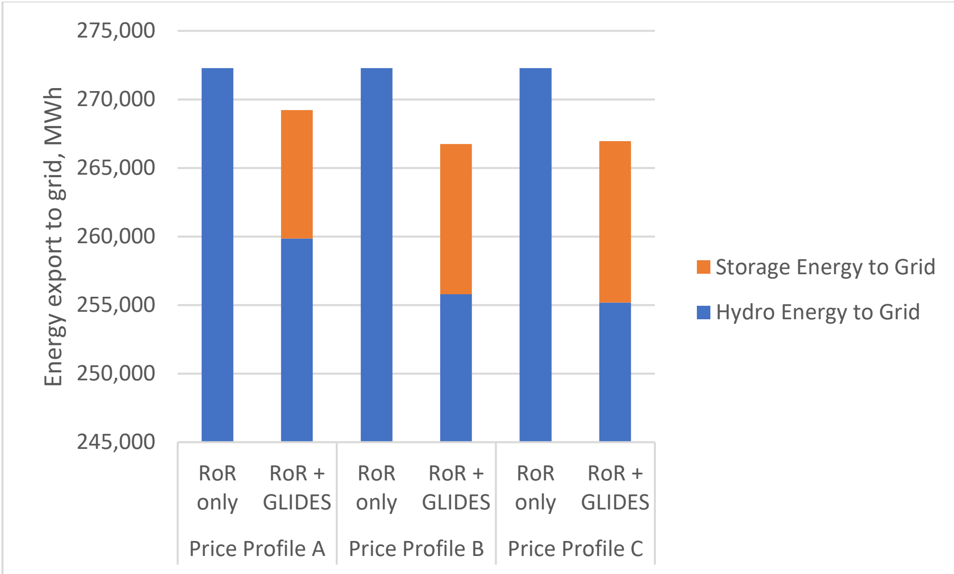

Figure 23. Forecast total annual energy export to the grid of the four RoR plants with and without GLIDES for each price profiles

Although with GLIDES the total energy export to the grid is lower, the revenue is higher. Breakdown of the revenue is shown in Figure 24. A relatively small fraction of total hydropower generation is used to charge GLIDES, resulting in significant overall payback in ancillary service sales and associated market revenues.

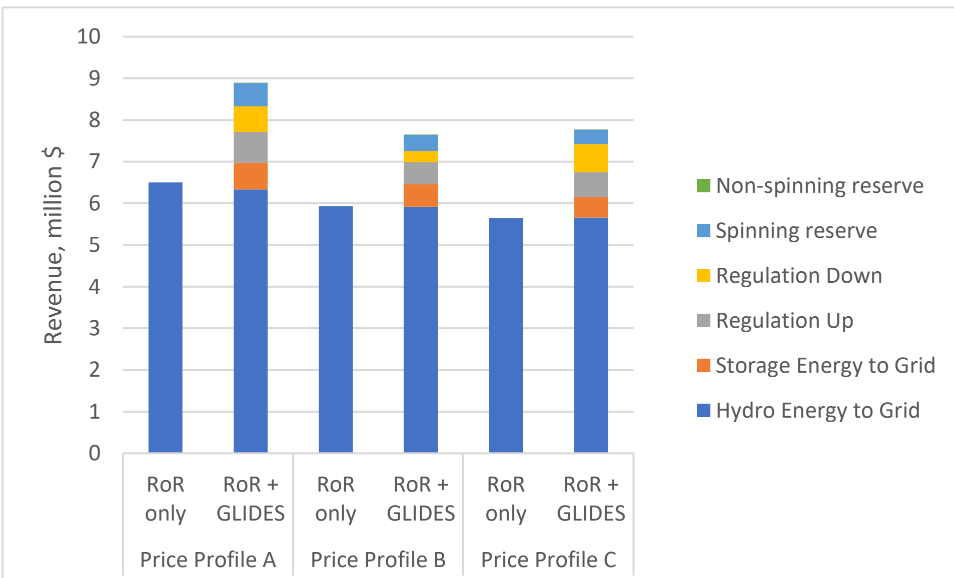

Figure 24. Annual summary results of revenue streams for different price profiles

The first cost of GLIDES was estimated using the model described is section 3.1 of this report and the payback period was calculated. For the GLIDES system size that was used in this use case (1 MW/4 hours (4MWh)), 610 15-meter-long pipe segments with maximum pressure of 145 bars and total volume of 6.25×10^3 liters are required. The total GLIDES first cost and the payback period are reported in

Table 9. The first cost associated with each 4 MWh system has been multiplied by 4 to account for the 4 powerplants studied in each price profile.

Table 9. Return of investment

	Price Profile A	Price Profile B	Price Profile C
Total Capital Cost ($)	11,375,522		
Total Revenue ($)	8,892,777	7,644,468	7,770,772
GLIDES Revenue ($)	2,391,486	1,713,970	2,122,400
Payback (Years)	4.76	6.64	5.36

The total first cost for the 4 1MW/4-hour GLIDES systems is almost $11.5M. The payback ranges from almost 5 to 7 years depending on the price profile. This estimated payback does not include any grants and it is much shorter than the useful lifespan (>40 years) of GLIDES.

5.0 Conclusion and Commercialization Pathways

The Ground-Level Integrated Diverse Energy Storage (GLIDES) is a novel modular pumped storage hydropower energy storage technology that was invented and demonstrated at Oak Ridge National Laboratory (ORNL) and is patented under US10519923. GLIDES stores energy by pumping liquid into pre-pressurized high-pressure vessels to compress gas inside the vessels. To dispatch the stored energy, the water under high pressure inside the vessels is discharged through a prime mover that spins an electrical generator. GLIDES first cost of hardware ranges from 350 to 600 $/kWh depending on the type of pressure vessels used: carbon steel, carbon fiber or high-pressure pipe segments. The cost is much lower if abandoned pipelines or underground caverns are used as the high-pressure reservoir. After the initial development of proof-of-concept prototype, work was focused on improving the technoeconomic value of GLIDES through increasing its energy density, RTE and lowering its first cost. The latest laboratory-scale prototype achieved an energy density of 1.2 kWh/m^3, with potential energy density of 1.7 kWh/m^3 possible with optimized machinery.

To quantify the economic performance of GLIDES, several use cases suitable for small-, medium- and large- scale GLIDES analyzed technoeconomically. A small-scale GLIDES was simulated as a local energy market interface between the grid and three buildings, each with PV generation. GLIDES was used for electricity price arbitrage. It was shown that GLIDES can be profitable while saving on utility bills for the buildings. A medium scale GLIDES was simulated as the energy storage for an electric vehicle PV-powered charging station. A model was developed to quickly calculate the optimal GLIDES capacity and predict the annual revenue based on PV generation, number of charging slots and vehicles arrival rate (cars/day). A large-scale GLIDES was simulated as integrated to a run-of-river (RoR) plant to enable them to provide grid services. Simulations were run for 4 cascaded RoR plants in Idaho Falls. A 1MW/4-hour GLIDES system was integrated to each plant. The simulations predicted a 28 to 37% increase in revenue due to grid services revenues and a 5 ~ 7-year simple payback period, which is much shorter than the useful lifetime of GLIDES. By virtue of its working principle, GLIDES is excellently poised to provide value to hydropower plants with no storage reservoirs not only in terms of revenue but also by serving as water storage.

The next step toward commercializing GLIDES is to demonstrate a full-scale pilot. The goal of a demonstration is to raise the technology readiness level (TRL) of GLIDES from TRL 5 (Laboratory scale, similar system validation in relevant environment) to TRL 8 (Actual system completed and qualified through test and demonstration). This increase in TRL de-risks the technology as it transitions from laboratory environment to actual implementation. Currently, the major potential technical barrier to deploying GLIDES is developing optimized prime mover or reversible pump-prime-mover for the high working pressure of GLIDES. Commercially available options may exist that could be tweaked specifically for this application. This could be done within a deployment project and does not necessarily need to be its own development endeavor.

Currently, two private entities, one US based and one international, have officially applied to license GLIDES and are currently in discussion with the ORNL Technology Transfer Office. Meanwhile, the current focus is on securing a demonstration site, preferable for a large-scale deployment. As part of the commercialization efforts, the GLIDES team participated in the DOE Energy I-Corps Cohort 13. Through the program, the team conducted 70 interviews representing various stakeholders: electric utilities, research and development institutes, government, water authorities and energy projects developers. The interviews were aimed at understanding what pain points stakeholders have and how GLIDES, as an energy storage technology, can relieve those pain points. Through the insights we collected from those interviews, we determined that regulated vertically integrated utilities were GLIDES most favorable entry point to the energy market.

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7.0 Appendix

7.1 Idaho Falls RoR plants generation data

A sample of the hydropower plant power generation data in Section 4.3 is attached here for illustration purpose. The data has 5 min time resolution, therefore there is 24192 (84 days × 288 timesteps) records totally.

	A	B	C	D	E
1	Datetime	Total Hydro Generation, Lower Plant (MWi)	Total Hydro Generation, City Plant (MWi)	Total Hydro Generation, Upper Plant (MWi)	Total Hydro Generation, Gem State (MWi)
2	2006-01-04 00:00:00	5.006	4.165	4.445	10.678
3	2006-01-04 00:05:00	5.006	4.165	4.445	10.678
4	2006-01-04 00:10:00	5.006	4.165	4.445	10.678
5	2006-01-04 00:15:00	5.006	4.165	4.445	10.678
6	2006-01-04 00:20:00	5.006	4.165	4.445	10.678
7	2006-01-04 00:25:00	5.006	4.165	4.445	10.678
8	2006-01-04 00:30:00	5.006	4.165	4.445	10.678
9	2006-01-04 00:35:00	5.006	4.165	4.445	10.678
10	2006-01-04 00:40:00	5.006	4.165	4.445	10.678
11	2006-01-04 00:45:00	5.006	4.165	4.445	10.678
12	2006-01-04 00:50:00	5.006	4.165	4.445	10.678

7.2 Price profiles

Similarly, the different market service data of Price profile A in Section 4.3 is illustrated here with same time resolution and record number.

	A	B	C	D	E	F
1	Datetime	Price: Energy ($/MWi)	Price: RegUp ($/MWi)	Price: RegDn ($/MWi)	Price: Spin ($/MWi)	Price:NonSpin ($/MWi)
2	2006-01-04 00:00:00	2.0558	0.3517	0.7226	0.2083	0.0075
3	2006-01-04 00:05:00	2.9690	0.3517	0.7226	0.2083	0.0075
4	2006-01-04 00:10:00	2.5602	0.3517	0.7226	0.2083	0.0075
5	2006-01-04 00:15:00	2.1420	0.3517	0.7226	0.2083	0.0075
6	2006-01-04 00:20:00	2.9742	0.3517	0.7226	0.2083	0.0075
7	2006-01-04 00:25:00	2.6646	0.3517	0.7226	0.2083	0.0075
8	2006-01-04 00:30:00	2.5517	0.3517	0.7226	0.2083	0.0075
9	2006-01-04 00:35:00	2.9822	0.3517	0.7226	0.2083	0.0075
10	2006-01-04 00:40:00	2.5749	0.3517	0.7226	0.2083	0.0075
11	2006-01-04 00:45:00	2.6450	0.3517	0.7226	0.2083	0.0075
12	2006-01-04 00:50:00	2.5325	0.3517	0.7226	0.2083	0.0075
13	2006-01-04 00:55:00	2.4911	0.3517	0.7226	0.2083	0.0075
14	2006-01-04 01:00:00	2.6083	0.1992	0.5025	0.0692	0.0075
15	2006-01-04 01:05:00	2.6665	0.1992	0.5025	0.0692	0.0075

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