PART 1- Techno-Economic Analysis of a Grid Scale Ground-Level Integrated Diverse Energy Storage (GLIDES) Technology[1]

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Key Words

GLIDES, Energy storage, Pumped-hydro storage, Compressed air, Energy storage cost analysis, Cost reduction.

Abstract

In this paper, a techno-economic model / cost reduction analysis of a low-cost, dispatchable / scalable, efficient Ground-Level Integrated Diverse Energy Storage (GLIDES) system is analyzed, along with a review of existing state-of-the-art energy storage technologies. The introduced technology, GLIDES, which was invented at the Oak Ridge National Laboratory (ORNL), stores energy by compression and expansion of air using water as a liquid piston inside high-pressure reservoirs. GLIDES is introduced by combining Pumped Hydroelectric Storage (PHS) and Compressed Air Energy Storage (CAES) technologies. By replacing inefficient gas compressor and turbine with higher efficiency liquid turbomachines for liquid-piston compression/expansion, GLIDES achieves higher roundtrip efficiency than other gas compression-based energy storage technologies and is a scalable energy storage system. For cost reduction purposes, various pressure reservoirs including steel vessels, carbon fiber vessels, pipe segments, and underground pressure reservoirs are analyzed in this paper. Based on the analyzed data using the models discussed in this paper, energy storage costs as low as *~$14/kWh* and *~$346/kWh* (roundtrip efficiency (RTE) ~80%) can be achieved for a grid-scale GLIDES using depleted oil/gas reservoirs and high-pressure pipe segments respectively.

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Nomenclature

Abbreviations		T	Temperature $[K]$
ED	Energy Density $[kWh/m^3]$	t	time [s]
RTE	Roundtrip Efficiency	A	Heat transfer Area $[m^2]$
PHS	Pumped Hydroelectric Storage	UA	overall heat transfer coefficient $[W/K]$
CAES	Compressed Air Energy Storage	$\dot{m}$	mass flow rate $[kg/s]$
FES	Flywheel Energy Storage	ρ	Density $[kg/m^3]$
LIB	Lithium-Ion Battery	η	Efficiency
FBES	Flow Battery Energy Storage		
PD	Positive Displacement	G	Generator
CF	Carbon Fiber	P	Pump
Bcf	Billion cubic feet	M	Motor
DOE	Department of Energy		
ORNL	Oak Ridge National Laboratory	**Indices**	
GLIDES	Ground-Level Integrated Diverse Energy Storage	v	at constant volume
		G	of gas
Symbols		L	of liquid
m	mass $[kg]$	amb	of ambient air
p	pressure $[bar]$	T	of tank walls
n	Polytropic constant	i	inner
E	Energy $[kWh/m^3]$	o	outer
V	Volume m^3	avg	average
c	specific heat capacity $[J/kg.K]$	max	maximum
h	heat transfer coefficient $[W/m^2K]$	min	minimum

1 Introduction

Grid modernization is vital to the nation's safety, economy, and modern way of life. Grid modernization can reduce the societal cost of power outage by more than 10%, decrease the cost of reserve margins by 33%, and reduce the cost of wind and solar integration by 50%, providing more than $7 billion in annual benefits for the US economy [1]. On the other hand, with the increase in the release of greenhouse gases into the atmosphere and their effect on the environment, the shift from fossil fuels to renewable energies is more critical now than ever before. In 2017, around 63% of the world's total electricity production was from fossil fuels, 20% from nuclear energy and around 17% from renewable energy sources [2].

Based on the Renewables 2018 Global Status Report by the Renewable Energy Policy Network for the 21st Century (REN21), with the commitment to phase out coal power by 2030, more than 20 countries including Italy, Mexico, and the United Kingdom launched the Powering Coal Alliance in 2017. Along with these countries in 2017, China, the United States, and Europe provided nearly 75% of the total global investment in renewable power and fuels [3]. In addition, with the passage of US Senate Bill 100 in 2018, electric utilities and other service providers are required to increase the amount of electricity generated by renewable energies from 50% to 60% by 2030 and the state of California is required to phase out coal power and replace it with clean sources to produce 100% of its power by 2045 [4]. The challenge with renewable energies is the variability in their output, which is due to their availability (e.g., lack of sunlight at night or lack of wind). Given the unpredictability of electricity demand, the output variability of the renewable energies, and the need for a power supply to meet the demand, the concept of energy storage is critical.

Given the limitations associated with intermittent renewable energies and to avoid grid instability, developing low-cost, efficient energy storage systems is critical and can provide many benefits. For example, energy from renewable sources, such as wind and solar, can be stored when available and used when those sources are unavailable or the price of electricity is high (peak shaving); stored when the demand is lower than the supply, such as nights when low-cost power plants continue to operate. Peak shaving is a technique used to reduce power consumption during high-demand periods and has the potential to lower the consumer's electric bill. Energy storage technologies can both discharge power quickly and slowly depending on the technology. Energy storage is valuable in grid stabilization, beneficial in electric vehicles, during power outages, in natural disasters, and in areas located away from the grid (e.g., islands and microgrids). To date, there are 1,267 energy storage projects worldwide with a total of around 171 *GW* of energy storage, with electrochemical technology (batteries) as the leading technology with the highest number of projects [5].

2 State-of-the-art Energy Storage Systems

To promote the integration of the expected growth in renewables into the electricity generation mix and grid modernization, various energy storage technologies have been developed. These technologies can be classified into four major categories: mechanical, electrical, chemical, and electrochemical [6]. The main characteristics used to compare energy storage technologies are rated power, energy capacity, energy density (ED), round-trip efficiency (RTE), and energy cost in *$/kWh*. Rated power is the maximum instantaneous power the system can output (*kW, MW, GW, etc*.); however, since the energy stored in the system is finite, the time in which the system can output the maximum instantaneous power until all energy is discharged plays an important role. Energy capacity is the numerical integration of the instantaneous power over the time it takes to completely discharge the energy stored in the system. Energy density (ED) is the amount of energy stored per unit of volume of the storage system. Roundtrip efficiency (RTE) is the ratio of the total energy that can be extracted from the system through discharging to the energy needed to charge the system to its full energy capacity. Many energy storage technologies have been deployed to date. Some of the existing energy storage technologies include but are not limited to those discussed below.

2.1 Mechanical Energy Storage

Some of the mechanical energy storage technologies include Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES), and Flywheel Energy Storage (FES). The technical and economical characteristics of these energy storage technologies are included in Table 1.

2.1.1 Pumped Hydroelectric Storage (PHS)

Pumped hydroelectric storage is the most widely used large-scale electrical energy storage. PHS technology accounts for around 97% of the world's electricity storage [7]. This technology converts electrical energy to potential energy using two water reservoirs at different elevations, a unit to pump water to the higher elevation, and a turbine to generate electricity.

During charging, a hydraulic pump is used to pump water from a lower reservoir (e.g., a lake or river) to a higher water reservoir (e.g., pond). During discharge, the elevated water can be released back into the lower reservoir. The water spins a hydraulic turbine that drives an electric generator to generate electricity [8,9].

Pumped hydroelectric storage has a relatively low capital cost, high roundtrip efficiency, and more than 40 year lifetime. The capacity of this system solely depends on the difference in elevation between the two reservoirs and the size of the reservoirs. The main disadvantage of this technology is its limited expansion prospect in the United States because most of the favorable sites have already been developed. Pumped hydroelectric storage also suffers from scalability and geographical limitations [8,9].

2.1.2 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) stores electrical energy in the form of high-pressure air using gas compressors. The compressed air is stored in a container (i.e., underground caverns or aboveground tanks), and a multi-stage turbine is employed to dispatch the stored energy.

During charging, CAES use gas compressors to compress air into an underground cavern or aboveground pressure reservoir. During discharging, the compressed air is expanded through a high-pressure gas turbine. The air is then mixed with fuel, and the mixture is combusted and expands through a low-pressure gas turbine. The low- and high- pressure turbines are connected through a common shaft to a generator to generate electricity.

There are only two operating CAES facilities in the world. Both systems are cavern based. The first ever CAES plant built is in Huntorf, Germany. It uses two salt dome-based caverns as the storage reservoirs. The other operating CAES is in the United States, in McIntosh, Alabama. It uses one salt dome–based cavern. CAES technology provides good part-load performance and a reasonable response speed. However, it suffers from low roundtrip efficiency due to the usage of gas turbomachines and also suffers from geographical limitations. High construction cost is the major barrier to deploying large-scale CAES plants [8,9].

2.1.3 Flywheel Energy Storage (FES)

Flywheels have been used for centuries to store energy in the form of kinetic energy. A flywheel energy storage system consists mainly of a flywheel, a reversible motor/generator, and an evacuated chamber. These systems can be classified as low and high speed. The flywheels themselves are usually made of steel and an advanced composite material such as carbon fiber.

During charging, the flywheel is spun by an electric motor. During discharging, the rotational energy of the flywheel is then used to spin the same motor, which now acts as a generator, to generate electricity.

The advantages of FES include long lifetime, high roundtrip efficiency, and relatively quick charging. Normally, FES systems can supply power for a short period of time. Therefore, they are not used as standalone backup power unless they are used with other energy storage technologies. Other disadvantages of this technology include idling losses during standby time and the need for a vacuum chamber. Flywheel malfunction during rotation is common and is usually caused by the propagation of cracks through the rotors [8–10].

2.2 Electrochemical Energy Storage (Batteries)

Electrochemical energy storage batteries have different chemistries and include lead acid, lithium ion, sodium-based, nickel-based, and flow batteries. The first large-scale battery storage installation in the United States entered service in 2003 using nickel-based and sodium-based batteries [11]. By the end of 2017, 708 MW of large-scale battery storage was in operation in the United States [12]. Some of the Electrochemical Energy Storage technologies include but are not limited to Lead Acid Batteries, Lithium-ion Batteries, Sodium-Sulfur Batteries, and Flow Battery Energy Storage. The technical and economical characteristics of these energy storage technologies are also included in Table 1.

2.2.1 Lead Acid Batteries

Lead acid batteries use two electrodes—one is composed of highly porous lead dioxide (PbO_2) and the other of finely divided metallic lead (Pb). The lead-dioxide electrode is the positive electrode, and the metallic lead is the negative electrode. The two electrodes are submerged in an electrolyte solution of dilute aqueous sulfuric acid. The negative electrode reacts with the hydrogen sulfate ion (HSO_4^-) of the electrolyte and produces lead sulfate ($PbSO_4$), hydronium ions (H_3O^+), and electrons (e^-). The positive electrode reacts with the hydrogen sulfate ion of the electrolyte, hydronium ions, and electrons to produce lead sulfate and water.

Lead acid batteries are the most popular low-cost batteries. Their RTE is around 70%. The disadvantages of these batteries, compared to other battery technologies, include relatively low cycle life (50–500 cycles), and the possibility of corrosion [10].

2.2.2 Lithium-ion Batteries

Lithium-ion battery (LIB) technology is based on the use of lithium-intercalation compounds. A cathode, the electrode where a reduction reaction takes place and electrons enter the cell, is a lithiated metal oxide (an oxide due to higher potential) that is often characterized by a layered structure. An anode, where an oxidation reaction takes place, is made of graphitic carbon which holds lithium in its layers. Both electrodes are capable of reversibly inserting and removing lithium ions from their structure.

Lithium-ion batteries outperform other electrochemical energy storage technologies by a factor of 2.5 in terms of energy capacity while providing high specific power. Over the last decade, the energy density of lithium-ion batteries has improved from 100 kWh/m^3 to around 730 kWh/m^3 [13]. The high energy density, around 97% roundtrip efficiency, relatively long life, and rapid charging of lithium-ion batteries have made them the first choice for powering electric vehicles [6,8,9]. Lithium-ion batteries suffer from degradation of maximum charge storage at high temperatures, thermal runaway and capacity loss when overcharged, and chemical and fire hazards [10].

2.2.3 Sodium-Sulfur Batteries

Sodium-sulfur batteries are an energy storage technology with the potential for use in grid support due to their long discharge period. Sodium-sulfur batteries use molten sodium as the anode (negative electrode), molten sulfur as the cathode (positive electrode), and beta alumina as the conducting solid electrolyte. These batteries operate at a temperature range of $270℃$ to $350℃$.

Hazardous materials, including metallic sodium, which is combustible when exposed to water, are used in sodium-sulfur batteries. This requires sodium-sulfur batteries construction to be airtight, double-walled, and sealed in stainless-steel enclosures. These enclosures contain arrays of sodium-sulfur cells to mitigate fire and to anchor the cells. These cells are sealed and surrounded with sand [10].

2.2.4 Flow Battery Energy Storage (FBES)

Flow batteries can be classified to redox flow batteries and hybrid flow batteries. The power of flow battery energy storage systems, unlike other electrochemical technologies, is independent of its storage capacity and is determined by the number of cells in the stack and the size of the electrodes used. The storage capacity of these systems is based on the concentration and the volume of the electrolyte used, meaning the system capacity can be increased by simply increasing the volume of reactants used or by increasing the electrolyte concentration [9]. Redox flow batteries use two circulating soluble redox couples as the electroactive species contained in external liquid electrolyte tanks. The simplicity of the reactions is distinct from other battery chemistries. Other batteries typically involve phase change, electrolyte degradation, and electrode morphology changes. There have been few field demonstrations of redox-flow batteries to date. The electrolytes, the electrodes, tanks, pumping systems, structure, power electronics, and controls have a longer lifespan than the cell stack, making the cell stack the life-limiting component of redox-flow batteries. Other drawbacks include nonuniform pressure drops (pressure drop due to the flow of electrodes in channels) and the limitation in the reactant mass transfer, causing low system performance, high manufacturing costs, and low energy density [6,9,10].

3 US Department of Energy’s Energy Storage Goal

The DOE’s 2010 “ARPA-E’s Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program [14] focused on development of low-cost storage technologies for the electric grid. Specifically, GRIDS aimed to address the challenge of renewable generation ramping. Initiated in 2010, ARPA-E’s GRIDS program is aimed at developing new storage technologies at a capital cost of less than *$*100 per *kilowatt-hour* that can scale to store *megawatt-hours* of electricity and be used at any location on the grid”[15]. Therefore, there is a need for a low-cost high-RTE high-energy-density dispatchable energy storage system that can meet the DOE’s target.

Technology	ED (kWh/m^3)	Rated (MWh)	Lifetime (Years)	RTE %	Discharge Time ($hours$)	Energy cost ($\$/kWh$)
PHS [16]	0.5–2	500–800	40–60	70–85	1–24, 6–10	5–100
CAES [16]	2–6	~ < 1000, 580 & 2860	20–40	42–54	1–24, 8–20	2–120
Flywheel [16]	20–80	1000–2000	~15+	90–95	8 s, 15 s–15 min	1,000–5,000
Lead-acid [9,17]	50–100	0.001–40	5–15	63–90	< 10	120–600
Li-ion [9,13]	240–730	0.004–10	5–15	90–99	~1–8	150–1300
Na-S [17]	150–300	0.4–245	10–15	75–90	~1	250–500

Table 1. Technical and economical characteristics of energy storage technologies.

4 The GLIDES Technology

Ground-Level Integrated Diverse Energy Storage (GLIDES) is an energy storage system that was invented at the Oak Ridge National Laboratory (ORNL) [18]. GLIDES stores energy by compression and expansion of air using water as a liquid piston inside high-pressure reservoirs. This system is a combination of CAES and PHS systems but is more efficient and has higher energy density than either technologies. As shown in Figure 1, the GLIDES system consists of a hydraulic motor, a hydraulic pump, high-pressure reservoirs (i.e., pressure vessels), a hydraulic turbine, and an electrical generator. The high-pressure reservoirs in this system are sealed vessels. These high-pressure reservoirs are pre-pressurized with air to a certain pressure. The choice of this initial pressure is explained in section 5. During charging, an electric motor is run which drives a positive displacement (PD) hydraulic pump. The pump pushes water into the pressurized reservoirs. With the water volume increasing inside the high-pressure reservoirs, the air above the water is compressed, causing its pressure to increase. During discharging, water is discharged from the vessels, causing the air above the water column to expand. The water flows through a hydraulic turbine that drives an electric generator, and electricity is generated.

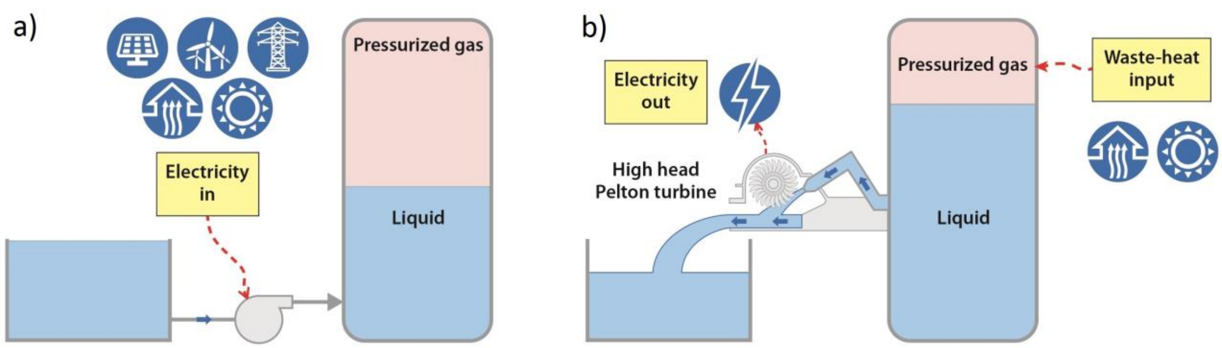


Figure 1. The invented GLIDES layout during (a) charging and (b) discharging [19].

Multiple lab-scale prototypes of GLIDES have been built at ORNL since 2015 [19] and a preliminary analysis of market potential of the GLIDES system including a mathematical model is introduced in [20]. The first prototype was built with a system nominal size of 3 kWh. This system consisted of an ambient pressure water storage, electric motor, electric generator, PD hydraulic pump, four steel high-pressure vessels, and a hydraulic Pelton turbine. Use of a hydraulic PD pump and Pelton turbine to charge/discharge the GLIDES system is one of the main advantages over CAES systems as no gas turbomachinery used, resulting in much higher roundtrip efficiency. The GLIDES system is easily scalable and dispatchable. The storage capacity can be increased by simply adding high-pressure storage volume (i.e. more vessels). The power capacity can be increased by using larger hydraulic machines, or several in parallel.

Manufacturing of steel vessels is largely non-automated. High manual labor and welding costs are associated with the manufacturing of steel vessels, causing them to be the dominant cost items of GLIDES. To meet DOE's target cost, several other pressure reservoirs are investigated in this paper including carbon fiber pressure vessels and high-pressure pipe segments. Carbon fiber vessels and high-pressure pipe segments are less expensive as they are mass manufactured semi-automatically and fully automatically, respectively. A techno-economic model of the GLIDES system (including a performance and a cost model), detailed results comparing pressure reservoirs, and further cost reduction opportunities are discussed in the next sections.

4.1 Cost Analysis Model

To compare the costs associated with the systems using steel vessels, carbon fiber pressure vessels, and high-pressure pipe segments, a cost analysis model was developed using the MATLAB programing package. The cost analysis model is an optimization model that solves for the lowest $\$/kWh$ system cost based on steel and carbon fiber pressure vessels and high-pressure pipe segments cost data gathered from manufacturers to build the desired GLIDES system size. As shown in Figure 2, the model takes the desired system size (kWh), an estimated roundtrip efficiency value, a pressure ratio (max/min pressure), and the pressure reservoir data (diameter, height, volume, maximum pressure, and price per vessel) from the manufacturers as the input. Using these inputs, based on the boundary work relation in a polytropic process ($W_b = \int_1^2 PdV\,, P = CV^n$) the amount of energy which can be stored per unit volume is calculated using Eq. (1). It then solves for the total storage volume needed based on the total energy storage needed and the desired system capacity (kWh) using Eq. (2). Based on Eq. (2) and vessel volume data from the manufacturer, the number of vessels needed to meet the desired system are calculated. Knowing the number of vessels needed and the cost per vessel, the cost model calculates the total cost and finds the pressure reservoir that results in the minimum cost. Based on the number of vessels, the cost model then adds the cost of the required piping, fittings, and valving along with the cost associated with selected motor/pump and turbine/generator. Summing up these costs, the model then once again looks for the option with the lowest total cost. As the data is different for different pressure reservoirs being studied, separate models were made for each system (pressure reservoir) type.

$$E_{st} = \frac{p_{max}\left(\frac{p_{max}}{p_{min}}\right)^{-\frac{1}{n}} - p_{min}}{1-n} \tag{1}$$

$$V_{st} = \frac{Rated\ Power \times storage\ time}{\eta_{RTE} \times E_{st}} \tag{2}$$

As discussed above, one of the inputs into the cost model is the pressure ratio. This is the ratio of maximum to minimum pressure of the working gas in the pressure reservoir, which is the range of pressure the system operates between. As the maximum allowable operating pressures of pressure reservoirs are set input data gathered from the manufacturers, the minimum pressure can be set to any pressure. This minimum pressure is the initial air pressure the system is pre-pressurized to. To determine the optimal pressure ratio (i.e., the best minimum pressure the system should initially be pressurized to), a physics-based performance model was developed. The physics-based performance model simulates the system transient profile (i.e., liquid/gas volume, temperature, pressure behavior) and the energy stored in the system at any time. As the required storage volume in the cost model is a function of the roundtrip efficiency, the cost model benefits from interaction with the performance model.

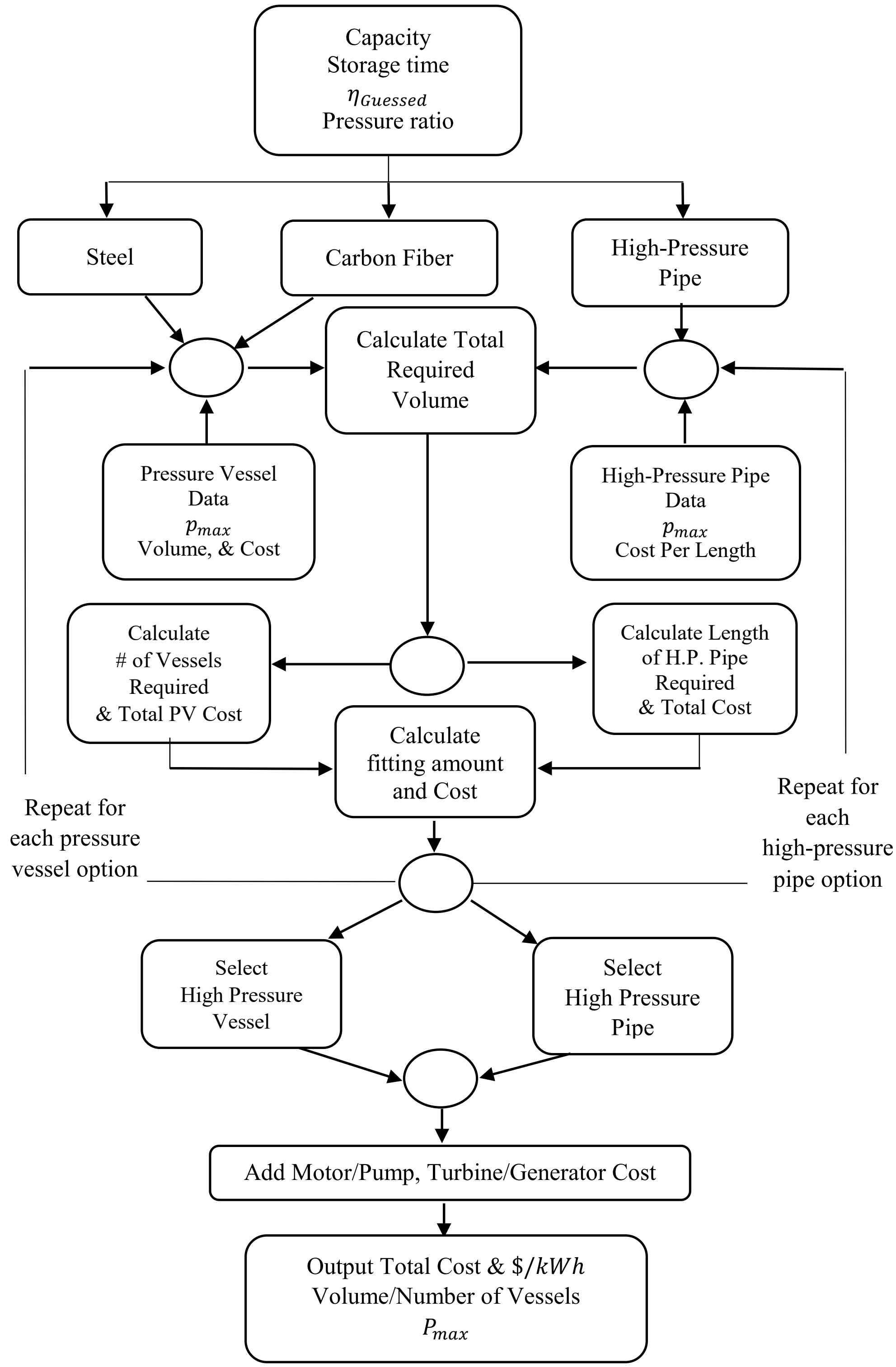


Figure 2. Cost Model flow chart [21].

4.2 Performance Model

To simulate the performance of the GLIDES system, a detailed physics-based performance model was developed [19,22]. For validation, the simulation data ([23]) was compared to experimental data collected from the first proof-of-concept prototype, as shown in Figure 3. Based on this comparison, it was found that the GLIDES system follows a Polytropic process with a constant of n = 1.2 (for compression/expansion process). As shown in Figure 3, it was also found that the water temperature remains almost constant during the entire process. Therefore, for simplicity, a simpler version of the previously studied physics-based performance model ([19]) is developed in this paper assuming a constant water temperature, no heat transfer between water and the tank walls, and a constant tank wall temperature. Furthermore, the heat transfer coefficients are solved for by matching the simulation data to the experimental data (assuming identical systems). Eq. (3) shows the gas energy equation. The term on the left is the rate of change in energy contained in the air at any time t; the first term on the right is the rate at which heat transfer occurs between the air and water; the second term on the right is the rate of heat transfer between the air and ambient through the tank walls; the last term on the right represents the rate of energy transfer due to boundary work [19].

a) b)

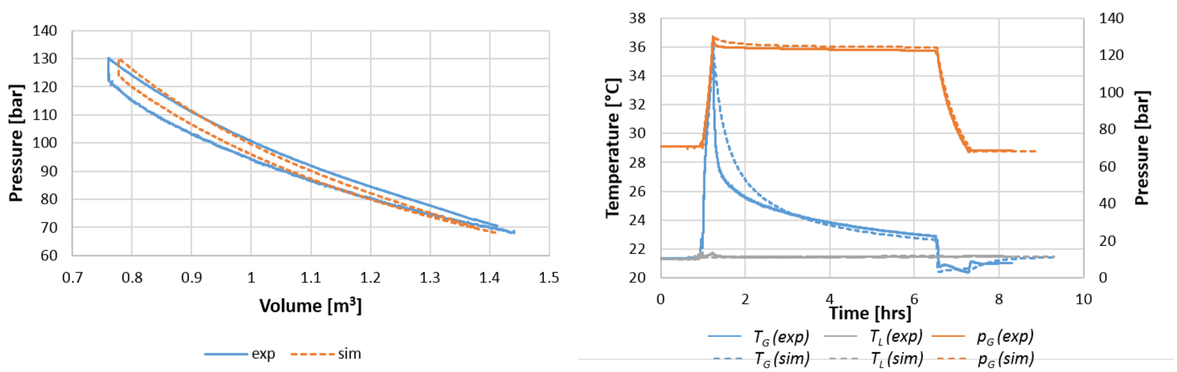


Figure 3. (a) GLIDES P-V diagram. (b) Temperature and pressure vs time. Experimental and simulations data [19,22].

$$m_G C_{v,G} \frac{dT_G}{dt} = -h_{G,L} A_{G,L} (T_G - T_L) - UA_G (T_G - T_{amb}) - P_G \frac{dV_G}{dt} \quad (3)$$

The continuity equation for the air is shown in Eq. (4). The term on the left is the time rate of change of the air volume, and the term on the right is volumetric flowrate of water causing the displacement of air, which as shown in Eq. (5) is calculated based on the continuity equation for water and the water density.

$$\frac{dV_G}{dt} = -\frac{\dot{m}_L}{\rho_L} \quad (4)$$

$$\frac{dm_L}{dt} = \dot{m}_L \quad (5)$$

UA_G in Eq. (3) represents the overall heat transfer coefficient, which is calculated based on the ambient air convection heat transfer coefficient, the conduction heat transfer coefficient through the tank walls, and the convection heat transfer coefficient of air inside the tanks. The overall heat transfer coefficient UA_G, can be calculated using Eq. (6).

$$UA_G = \frac{1}{\left(\frac{1}{h_{i,G} A_{i,G}}\right) + \left(\frac{t_T}{K_T A_{ave,G}}\right) + \left(\frac{1}{h_0 A_{0,G}}\right)} \quad (6)$$

Capital cost models are usually not strongly sensitive to the performance of the system. In GLIDES, capital cost and performance are highly interdependent on one another. Integrating the physics-based performance model with the cost model allows for sizing of a system with the lowest capital cost and highest roundtrip efficiency.

4.3 Entrance Model

To combine the manufacturers' data, the cost model, and the physics-based performance model, an entrance model was introduced. With overall system inputs of desired storage capacity (*kWh*) and an estimated value for the roundtrip efficiency, the cost model optimizes the system design for the lowest cost. The cost model outputs the selected pressure reservoir's parameters, maximum pressure, number of vessels, and total projected *$/kWh* capital cost. In taking the system parameters, maximum pressure, and the number of vessels from the cost model, the physics-based performance model simulates the gas/water behavior and outputs work and power profile and an updated roundtrip efficiency based on the performance of the selected system. The overall model then outputs the total system cost, the *$/kWh* cost, transient profile, and the updated roundtrip efficiency. The updated roundtrip efficiency is then fed back into the cost model to now run the calculations/optimization with an improved value for roundtrip efficiency. The system runs the loop until the lowest cost is found and a stope criteria for small change in the roundtrip efficiency is met and outputs the final values for cost, efficiency, and the transient profile.

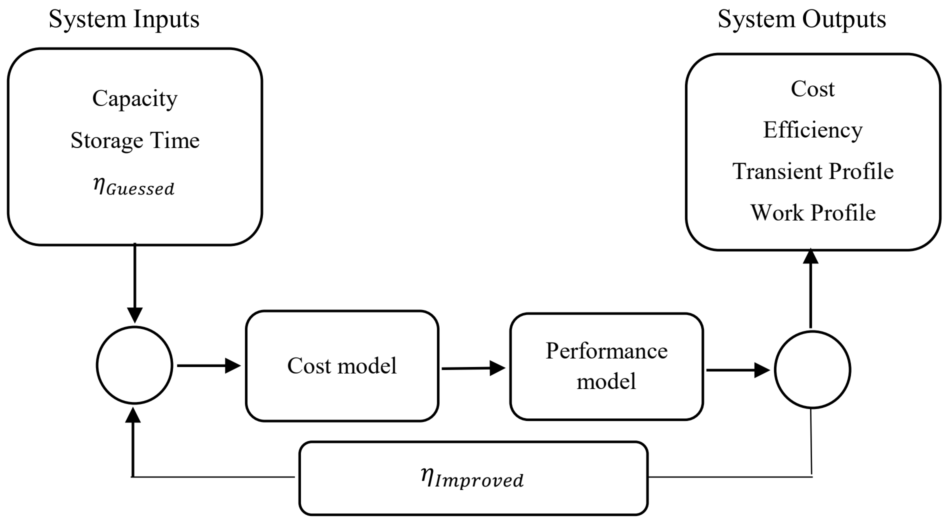


Figure 4. Overall model flow chart [21].

5 Results

Energy storage systems, depending on their scalability, can be used in both household and grid applications. To analyze the cost and performance of GLIDES for these two applications, a system was sized for steel, carbon fiber pressure vessels, and high-pressure pipe segments and for system capacities ranging from 10 *kW* (close to Tesla's Powerwall [24]) to 300 *MW* (close to that of a CAES plant). These systems were sized for storage hours ranging from 2 to 6 *hours* and pressure ratios ranging from 1.3 to 20.

As explained above, the only controllable parameters in this analysis are the type of the pressure reservoirs, the system's energy capacity, hours of storage, and pressure ratio (P_{max}/P_{min}). On the other hand, the goal of this analysis is to find the system with the highest energy density, highest roundtrip efficiency, and lowest cost. Therefore, to do this analysis, from the studied systems, the change in system cost per *kWh* with the change in the system size (*kWh*) and pressure ratio was significant. As anticipated, the total cost of the system increased with the increase in system size, but the *$/kWh* cost of the system decreased. Another interesting trend was the change in the system *$/kWh* cost and energy density with the change in pressure ratio. To analyze the change in *$/kWh* and the ED with the change in pressure ratio, these data were plotted on the same chart, with *$/kWh* on the left axis and ED on the right axis for a 100 *kW* system with 2, 4, and 6 *hours* of storage and pressure ratios ranging from ~1 to ~20. The system roundtrip efficiency did not change much and ranged between ~75–80%. As shown on the left axis of Figure 5, *$/kWh* system cost decreases between pressure ratios of ~1.3 and ~2.7 and increases from ~2.7 to ~20. The lowest *$/kWh* cost in this trend occurs at a pressure ratio of ~2.7. As shown on the second axis of Figure 5, the energy density of the said system increases between pressure ratios of ~1.3 to ~2.7 and decreases from ~2.7 to ~20. The highest ED of the system is measured at pressure ratio of ~2.7, at which the lowest cost occurs. A pressure ratio of 2.7 means that if the maximum allowable pressure of a pressure reservoir is ~200 *bars* (set by manufacturer), to have a system with the maximum ED and lowest *$/kWh*, each pressure reservoir (within the studied cases) best be pre-

pressurized to ~74 *bar* air pressure. This pressure ratio, as shown in Figure 5, is found to be the best pressure ratio for all the pressure reservoirs studied. Experimental results also suggest a polytropic constant of $n = 1.2$ for the GLIDES system. These data can be proved by differentiating Eq. (1) with respect to the P_{min}, which can give the optimum pressure ratio using Eq. (8) (using $n = 1.2$ polytropic constant), suggesting that the best pressure ratio for the system, at which the energy storage per unit volume is maximized, can be described as

$$\left(\frac{P_{max}}{P_{min}}\right)_{optimum} = n^{\left(\frac{n}{n-1}\right)} \qquad (7)$$

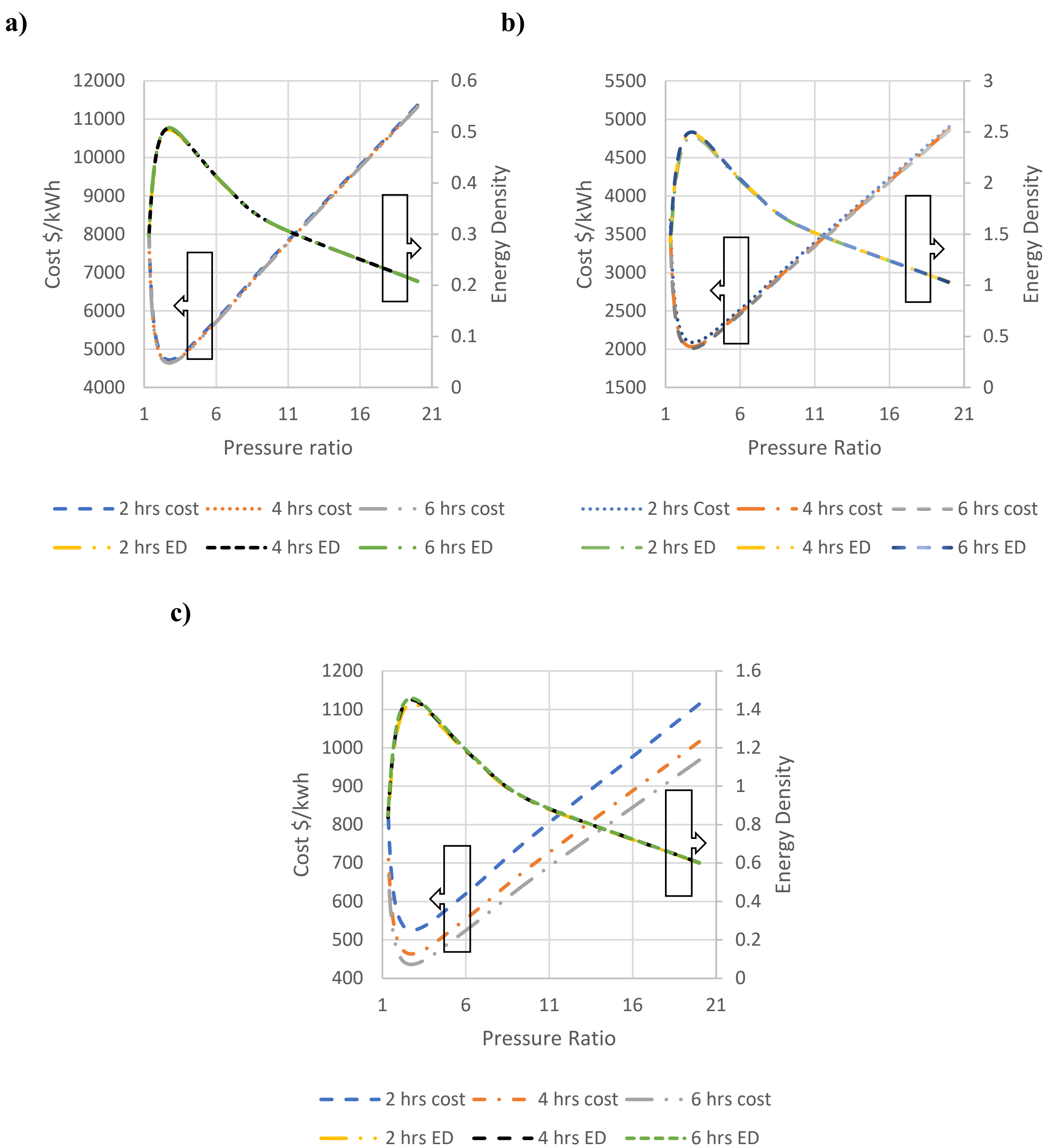


Figure 5. Parametric study, cost (*$/kWh*) and energy density vs. pressure ratio for the systems with (a) steel pressure vessels, (b) carbon fiber vessels, and (c) high-pressure pipe segments as the pressure reservoir [21].

5.1 Parametric Analysis

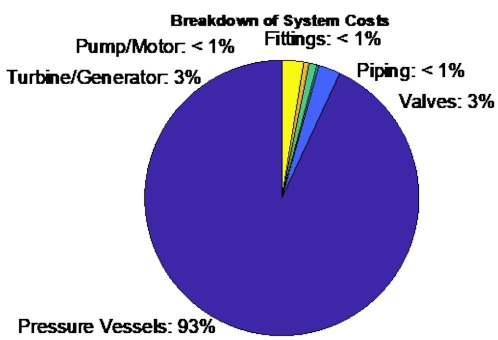
To analyze the cost of GLIDES at various scales, the cost of GLIDES using steel pressure vessels, carbon fiber pressure vessels, and pipe segments was analyzed in this section. Some detailed simulation data including system capacity, number of vessels, and cost are included in Appendix A, B, and C.

5.1.1 Steel Pressure Vessels

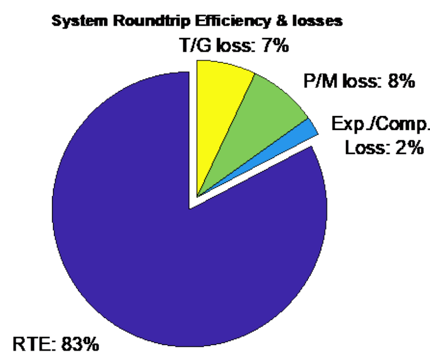
The cost of GLIDES using steel pressure vessels ranges from *$4,500/kWh* for a 300 *MW* and 6 *hours* system with a 2.7 pressure ratio to *$5,100/kWh* for a 10 *kW* and 2 *hours* system with a 2.7 pressure ratio.

The cost and efficiency of a 100 *kW* and 2 *hours* system and a 2.7 pressure ratio is analyzed. As shown in Figure 6(a), ~93% of the system cost is associated with the cost of the steel pressure vessels, followed by ~3% in turbine/generator cost, ~3% in valve cost, and ~1% in pump/motor, piping, and fitting costs. For the 200 *kWh* system studied, ~160 3,000-liter steel pressure vessels with a maximum pressure of 200 *bar* are needed to meet the storage requirements. A total cost of ~*$*1,200k and ~*$4,700/kWh* is calculated for this system. This total cost can be broken down into ~*$*1,190k in steel pressure vessel cost, ~$33k in turbine/generator cost, ~*$*8k in motor/pump cost, and ~*$*4k in fitting, valve, and piping cost. As explained above, RTE and ED are two important performance characteristics of any energy storage technology. A pie chart in Figure 6(b) shows the breakdown of efficiency losses in this system (a constant efficiency of 90% is assumed for the turbomachinery of the GLIDES system which has an RTE of ~83% with an energy density of ~0.51 kWh/m^3.

a)



b)



c)

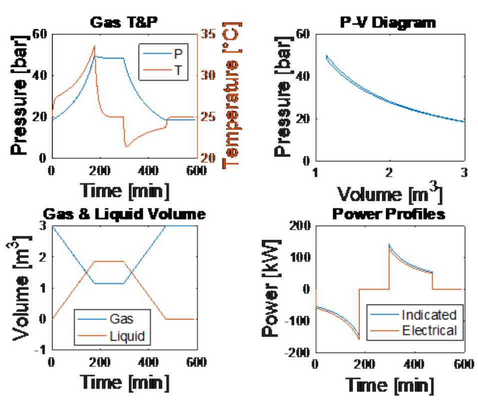


Figure 6. (a) System cost breakdown, (b) roundtrip efficiency/losses, and (c) performance of a 200 *kWh* system, steel pressure vessel.

5.1.2 Carbon Fiber Pressure Vessels

The cost of GLIDES using carbon fiber pressure vessels ranges from *$760/kWh* for a 10 *MW* and 3 *hours* system and a 2.7 pressure ratio to *$*1,000*/kWh* for a 100 *kW* and 1 *hour* system and a 2.7 pressure ratio.

The cost and efficiency of a 100 *kW* and 2 *hours* system and a 2.7 pressure ratio is analyzed. As shown in Figure 7(a), ~74% of the system cost is associated with the cost of the carbon fiber pressure vessels, followed by ~12% in turbine/generator cost, ~5% in valve cost, and ~8% in pump/motor, piping, and fitting costs. For the 200 *kWh* system studied, ~120 900-liter carbon fiber pressure vessels with a maximum pressure of 248 *bar* are needed to meet the storage requirements. A total cost of ~\$650k and ~*$*2,100*/kWh* is calculated for this system. This total cost can be broken down to ~*$*580k in carbon fiber pressure vessel cost, ~*$*33k in turbine/generator cost, ~*$*15k in valve cost, and ~*$*23k in pump/motor, fitting, and piping cost. The pie chart in Figure 7(b) shows the breakdown of efficiency losses in this system which has an RTE of ~74% with an energy density of ~2.45 *kWh*/m^3.

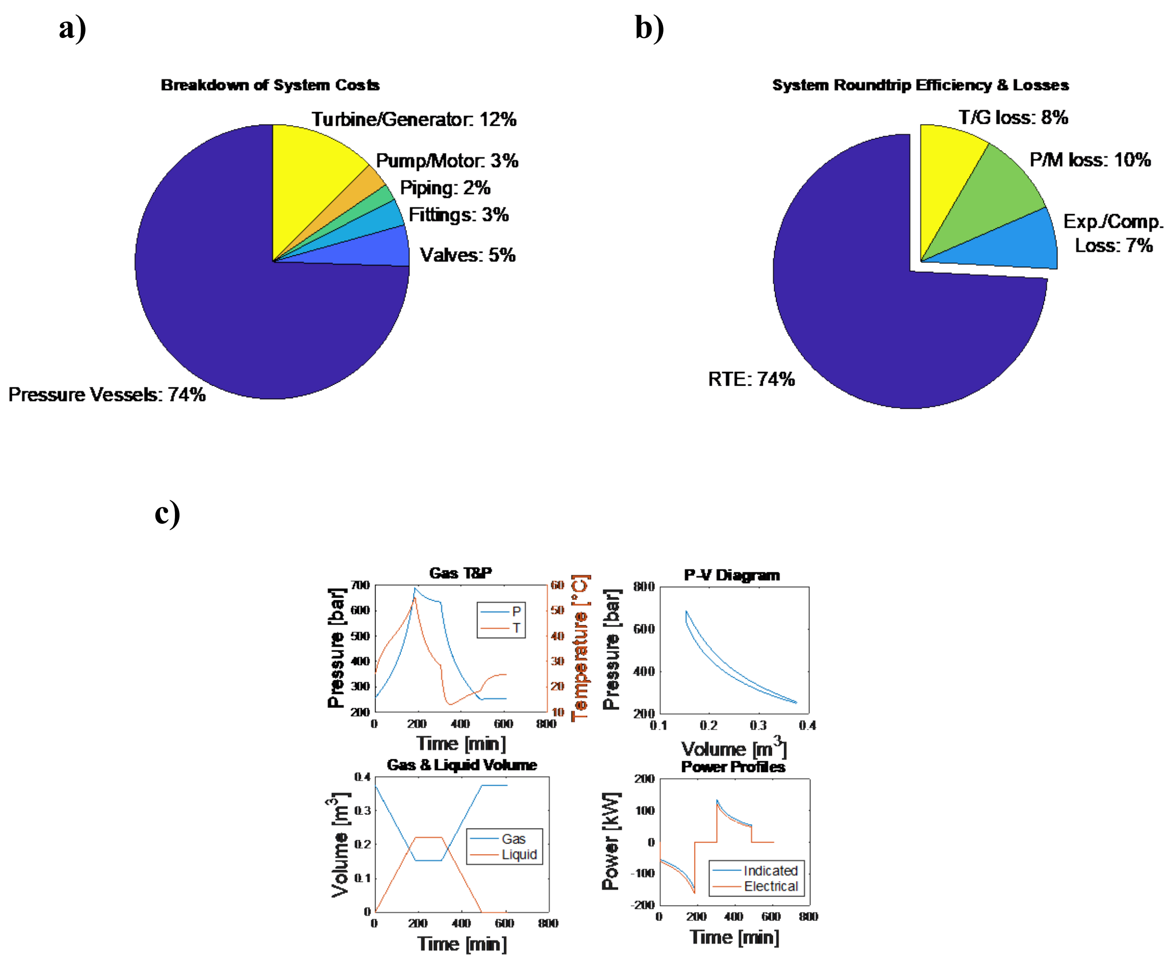


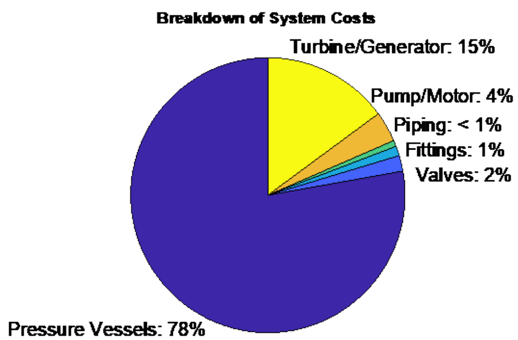
Figure 7. (a) System cost breakdown, (b) roundtrip efficiency/losses, and (c) performance of a 200 *kWh* system, carbon fiber pressure vessel.

5.1.3 High-Pressure Pipe Segments

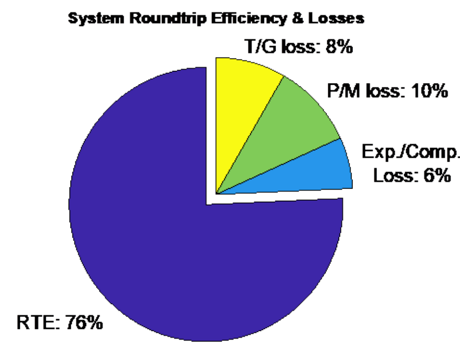
The cost of GLIDES using high-pressure pipe segments ranged from *$250/kWh* for a 300 *MW* and 6 *hours* system and a pressure ratio of 2.7 to *$1,100/kWh* for a 10 *kW* and 2 *hours* system and a 2.7 pressure ratio.

The cost analysis of a 100 *kW* and 2 *hours* system and a 2.7 pressure ratio is analyzed. As shown in Figure 8(a), ~78% of the system cost is associated with the cost of the high-pressure pipe segments, ~15% in turbine/generator cost, ~4% in motor/pump, and less than 1% in piping, fitting, and valve costs. For the 200 *kWh* system, ~32 30-meter-long pipe segments with a volume of ~6,200 *liters* and a maximum pressure of 145 *bar* are needed to meet the storage requirement. A total cost of ~*$225*k and ~*$715/kWh* is calculated for this system. This total cost can be broken down to ~*$176*k in pipe segment cost, ~*$33*k in turbine/generator cost, ~*$8*k in motor/pump cost, and ~*$8*k in fitting, valve, and piping cost. The pie chart in Figure 8(b) shows the breakdown of efficiency losses in this system which has an RTE of ~76% with an energy density of ~1.42 kWh/m^3.

a)



b)



c)

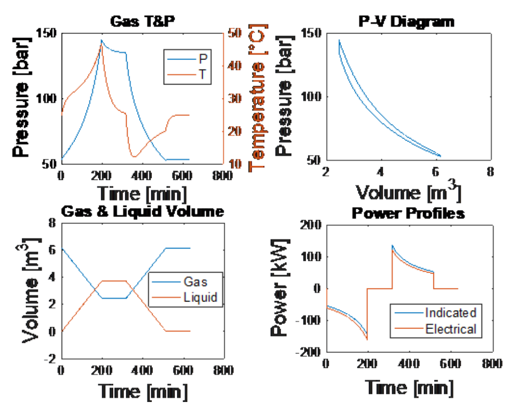


Figure 8. (a) System cost breakdown, (b) roundtrip efficiency/losses, and (c) performance of a 200 *kWh* system, high-pressure pipe segments.

6 Cost Reduction Opportunities

Based on the analyzed data using the models discussed in previous sections, energy storage costs as low as *~$346/kWh* can be achieved for a 60 MWh grid-scale GLIDES using high-pressure pipe segments (Appendix C). This system has an RTE of ~80% and an ED of ~1.46 kWh/m^3 using ~9,000 16-meter-long segments. For comparison, a grid-scale renewable photovoltaic (PV) field capable of producing the same amount of energy (60 MWh) uses around 50,000 PV panels (assuming 1.2 kWh/panel produced in 4 hours each day). As explained in the Results section, most of the cost associated with the GLIDES system is attributed to the pressure vessels. To farther reduce the cost of the system closer to DOE's target, other pressure reservoirs were analyzed including underground reservoirs and abandoned pipelines.

6.1 Underground Reservoirs

One cost-reduction option is to use the GLIDES technology underground. Underground reservoirs have been used for natural gas storage for decades [25]. A smaller footprint, larger reservoirs, and lower costs are possible advantages of taking GLIDES underground (Figure 9). Some of the underground reservoirs studied are discussed in this section.

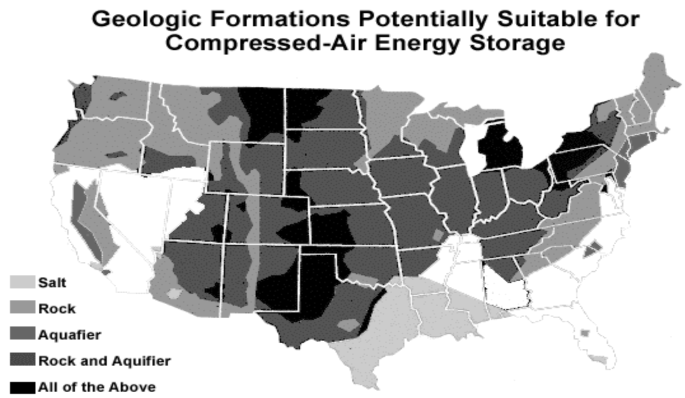


Figure 9. Geologic opportunities for underground storage size in the United States [26].

6.1.1 Depleted Oil/Gas Reservoir

GLIDES can use depleted oil/gas reservoirs (formed in porous rock) as the pressure reservoir. 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, or in some cases some wells are abandoned, and no operator is filed (especially for wells drilled in early 1980s). Depleted oil and gas reservoirs are the most common underground natural gas storage facilities [26]. 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 [25]. Around 2.3 million abandoned wells exist in the United States [27,28]. 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 [29]. Typical 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) [25]. Using equations (1 and 2), in a 1 billion ft^3 underground reservoir, assuming a maximum pressure range of 10–100 *bar* and around a $1 million cost (around 20 times higher than GLIDES using pressure vessels) associated with the turbomachinery (motor/pump, turbine/generator, and piping), a *$/kWh* cost of *$*13.6/*kWh* to *$*136.91/*kWh* can be achieved, respectively. A detailed cost analysis of using depleted oil/gas reservoir will be discussed in a subsequent publication.

6.1.2 Aquifers

Another pressure reservoir option for GLIDES is aquifers. They 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 in order 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. Elevation difference and maximum pressure needs to be studied to avoid problems. 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 the low flow rates, which cause 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 [25,29,30]. A number of aquifers have operated as natural gas storage reservoirs for many decades.

6.1.3 Salt Caverns

Salt caverns could be another underground storage reservoir option for GLIDES. Over the decades, with the oceans and lakes evaporating, the resultant leftover salt was buried underneath layers of dust. Solution mining is used for extraction of 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 [29,30]. Cavern sealing is not required in solution mined salt caverns due to their low permeability and self-healing characteristics [30]. 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. Some advantages of using salt caverns for GLIDES technology can include a very large reservoir volume, high safety standards, a much smaller footprint, a much higher RTE than CAES, and a much lower specific investment cost. Some of the disadvantages include the solubility of salt in water (if water is used as the working fluid), which would cause the cavern size and likewise the cavern pressure to change (working fluid/gas would be further investigated). The cost associated with the salt caverns can go upwards of *$*10 *million/Bcf* (*$*353 *million/Bm*^{3}) of working gas capacity. There are two working CAES plants in the world—one in Huntorf, Germany, and one in the United States in Alabama. The CAES plant in Germany consists of two salt caverns which can 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* permissible and operational maximum 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* [29–31].

Other mining options include hard-rock mining techniques, which can be used to create hard-rock caverns (Figure 10). 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 [30]. Hard-rock caverns are expensive, and therefore small scale would be more desirable. A detailed cost analysis of underground caverns will be discussed in a subsequent publication.

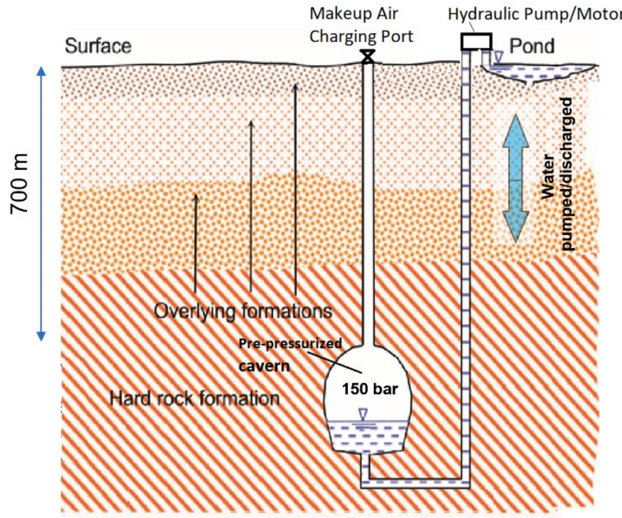


Figure 10. Hard rock cavern as underground reservoir for GLIDES.

6.2 Abandoned Pipelines, Vessels

Pipelines are said to be abandoned when an oil and gas company owner of the pipelines ceases operation and is no longer in need of the pipelines. Regardless of the owner's decision, the pipeline company is required to clean the pipes and if the pipes are to be left in place, the sides must be locked. These pipes could be adapted for use as pressure reservoirs for the GLIDES system. The major cost associated with these pipes mainly involves welding activities. The working pressure of the pipes depends on their thickness. A cost analysis of abandoned pipelines will be discussed in a subsequent publication.

7 Conclusion

A techno-economic analysis of a Ground-Level Integrated Diverse Energy Storage (GLIDES) system is discussed in this work. Multiple pressure reservoirs are described, most of which are being used for natural gas storage but can be used for systems like GLIDES, involving water and hydraulic turbomachinery. Based on the analyzed data using the models discussed in previous sections, energy storage costs as low as *~$14/kWh* and *~$346/kWh* (RTE ~80%) can be achieved for a grid-scale GLIDES using depleted oil/gas reservoirs and high-pressure pipe segments respectively. Underground energy storage reservoirs could mainly be used for grid-scale storage; pressure vessels and pipe segments could be used for smaller scale applications such as factories and households. Some advantages of using underground reservoirs include large storage reservoir (grid-scale) and lower *$/kWh* cost; a much smaller footprint compared to above ground reservoirs. Some of the disadvantages of using underground reservoirs include scalability, geographical location with limited access to water reservoirs or renewable energy plants (e.g., if using wind energy for the charging process), and hazards, including drinking water contamination. Further techno-economic analysis of underground reservoirs is needed to fully determine the associated charges.

8 Acknowledgments

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9 Appendix

APPENDIX A

TABLE OF PARAMETRIC RESULTS FOR GLIDES SYSTEM UTILIZING STEEL PRESSURE VESSELS

Capacity [kW]	Storage Time [hrs.]	Pressure Ratio	Round-trip Efficiency	Energy Density [kWh/m^3]	Electricity Output [kWh]	System Cost [$/kWh]	System Cost [$]	Storage Pressure Vessel Cost [$]	Number of Vessels
100	4	2.86	0.84	0.51	453	4,708	2,552,172	2,413,424	328
100	4	2.00	0.84	0.48	459	5,000	2,743,498	2,597,374	353
100	4	1.33	0.84	0.30	466	7,537	4,442,463	4,230,850	575
100	6	2.86	0.84	0.51	681	4,673	3,791,959	3,605,420	490
100	6	2.00	0.84	0.48	690	4,960	4,075,119	3,877,666	527
100	6	1.33	0.84	0.30	701	7,960	6,623,569	6,327,880	860
1,000	4	2.86	0.84	0.51	4,521	4,664	25,225,187	24,082,734	3,273
1,000	4	2.00	0.84	0.48	4,583	4,957	27,146,090	25,929,592	3,524
1,000	4	1.33	0.84	0.30	4,649	7,979	44,112,791	42,242,278	5,741
1,000	6	2.86	0.84	0.51	6,798	4,643	37,607,741	35,987,978	4,891
1,000	6	2.00	0.84	0.48	6,989	4,931	404,092,922	38,761,944	5,268
1,000	6	1.33	0.84	0.30	7,008	7,931	65,954,453	63,242,010	8,595
10,000	4	2.86	0.84	0.51	45,207	4,646	251,262,546	240,797,908	32,726
10,000	4	2.00	0.84	0.48	45,826	4,939	270,433,311	259,229,698	35,231
10,000	4	1.33	0.84	0.30	46,486	7,962	440,115,627	422,371,274	57,403
10,000	6	2.86	0.84	0.51	67,978	4,631	375,118,698	359,879,780	48,910
10,000	6	2.00	0.84	0.48	68,975	4,919	403,916,937	387,567,934	52,673
10,000	6	1.33	0.84	0.30	70,074	7,920	658,524,594	632,361,236	85,942

APPENDIX B

TABLE OF PARAMETRIC RESULTS FOR GLIDES SYSTEM UTILIZING CARBON FIBER PRESSURE VESSELS

Capacity [kW]	Storage Time [hrs.]	Pressure Ratio	Round-trip Efficiency	Energy Density [kWh/m^3]	Electricity Output [kWh]	System Cost [$/kWh]	System Cost [$]	Storage Pressure Vessel Cost [$]	Number of Vessels
100	4	2.86	0.78	2.49	458	2,074	1,215,889	1,115,100	236
100	4	2.00	0.78	2.33	461	2,213	1,300,464	1,195,425	253
100	4	1.33	0.80	1.43	462	3,563	2,071,589	1,927,800	408
100	6	2.86	0.79	2.50	690	2,040	1,783,039	1,653,750	350
100	6	2.00	0.79	2.34	697	2,172	1,912,389	1,776,600	376
100	6	1.33	0.80	1.45	703	3,492	3,071,564	2,877,525	609
1,000	4	2.86	0.78	2.49	4,567	2,033	11,882,893	11,117,925	2,353
1,000	4	2.00	0.78	2.33	4,603	2,172	12,743,568	11,935,350	2,526
1,000	4	1.33	0.80	1.43	4,623	3,521	20,464,768	19,268,550	4,078
1,000	6	2.86	0.79	2.50	6,885	2,013	17,544,443	16,494,975	3,491
1,000	6	2.00	0.79	2.34	6,961	2,145	18,847,893	17,732,925	3,753
1,000	6	1.33	0.80	1.45	7,029	3,465	30,449,593	28,751,625	6,085
10,000	4	2.86	0.78	2.49	45,660	2,017	117,842,168	111,150,900	23,524
10,000	4	2.00	0.78	2.33	46,020	2,156	126,448,918	119,325,150	25,254
10,000	4	1.33	0.80	1.43	46,221	3,505	203,675,843	192,671,325	40,777
10,000	6	2.86	0.79	2.50	68,853	2,002	174,487,518	164,949,750	34,910
10,000	6	2.00	0.79	2.34	69,602	2,134	187,492,168	177,300,900	37,524
10,000	6	1.33	0.80	1.45	70,279	3,454	303,504,193	287,483,175	60,843

APPENDIX C

TABLE OF PARAMETRIC RESULTS FOR GLIDES SYSTEM UTILIZING HIGH-PRESSURE PIPE SEGMENTS

Capacity [kW]	Storage Time [hrs.]	Pressure Ratio	Roundtrip Efficiency	Energy Density [kWh/m^3]	Electricity Output [kWh]	System Cost [$/kWh]	System Cost [$]	Storage Pipe Cost [$]	Number of 50 ft. Segments
100	4	2.86	0.78	1.45	476.74	608	372,821	315,782	61
100	4	2.00	0.78	1.36	489.03	639	398,643	340,104	67
100	4	1.33	0.80	0.84	501.35	951	599,422	530,383	109
100	6	2.86	0.79	1.46	720.08	563	514,934	450,395	91
100	6	2.00	0.79	1.37	739.53	591	552,394	485,856	99
100	6	1.33	0.80	0.85	761.00	886	842,891	760,602	162
1,000	4	2.86	0.78	1.45	4,770	464	2,844,626	2,515,408	610
1,000	4	2.00	0.78	1.36	4,887.60	489	3,051,026	2,708,808	662
1,000	4	1.33	0.80	0.84	5,011.77	741	4,670,415	4,222,697	1,084
1,000	6	2.86	0.79	1.46	7,197	436	3,988,584	3,585,866	904
1,000	6	2.00	0.79	1.37	7,392.55	459	4,290,837	3,868,369	983
1,000	6	1.33	0.80	0.85	7,609.62	698	6,636,768	6,055,800	1,617
10,000	4	2.86	0.78	1.45	47,697	365	22,361,173	20,026,655	6,097
10,000	4	2.00	0.78	1.36	48,875.54	385	24,031,548	21,566,530	6,619
10,000	4	1.33	0.80	0.84	50,115.97	589	37,138,167	33,619,399	10,834
10,000	6	2.86	0.79	1.46	71,972	346	31,618,995	28,549,727	9,036
10,000	6	2.00	0.79	1.37	73,925.48	364	34,066,043	30,798,525	9,829
10,000	6	1.33	0.80	0.85	76,094.81	558	53,065,085	48,213,817	16,164

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