Every Coal is a Goal: Gravity Batteries in West Virginia Mine Shafts

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BACKGROUND

Abandoned, decommissioned, and early retired underground coal mines in southern and northwestern West Virginia can be reclaimed for the construction of grid scale, long duration energy storage. Energy storage capacity is required to enable reliable electricity supply as renewable generation sources are added to the grid. This report outlines analytical energy capacity models for three gravity energy storage technologies. These models are then applied to mine shafts in West Virginia to determine energy storage capacity of the land using mine shaft dimensions, operational status, and extant infrastructure as inputs. The case study reveals an opportunity for at least 72 megawatt hours of energy storage via adoption of gravity energy storage systems in existing underground coal mines.

METHODS

Analytical models of energy storage capacity of long duration energy storage technologies are developepd for dry gravity energy storage, and a system of combined compressed air energy storage and dry gravity energy storage. These models are then applied to underground mining land in West Virginia identified through GIS databases and permitting information. The resulting mine shaft and technology scenarios depict energy storage capacities of 54, 68, and 72 megawatt hours.

LONG DURATION STORAGE TECHNOLOGY COMPARISON

Table 1

Technology	Power Capacity (MW)	Discharge Time (hrs)	Energy Rating (MWh)	Response Time	Land Use (m^2/kWh)	Lifetime (yrs)	Efficiency (%)
Flow Battery	0.01-10	4-24	0.1-100	millisecond		5-20 years	65-80
Thermal Storage	1-300	4-24	0.1-2000		0.03-1.2		
Pumped Hydro power	10-3000	10-100	100-20000	seconds-minutes	1.07	25-100	60-85
Solid Gravity Energy Storage	1-1000	4-24	4-10000	seconds	0.16	50+	80-92
Compressed Air Energy Storage	1-300	10-100	10-10000	3-10min	0.27-0.3	20-30	55-75

Mechanical and elastic energy storage technologies out preform chemical and electrochemical systems in power capacity, energy rating, and efficiency. Solid gravity energy storage is selected for modeling due to its large power capacity, long duration discharge time, modularity, lifetime, and system efficiency.

TECHNOLOGY MODELS

Figure 1 Shaft Gravity Energy Storage System (S-GES)

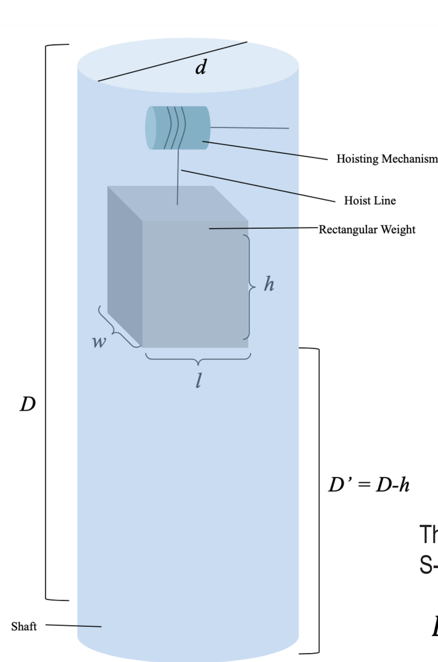
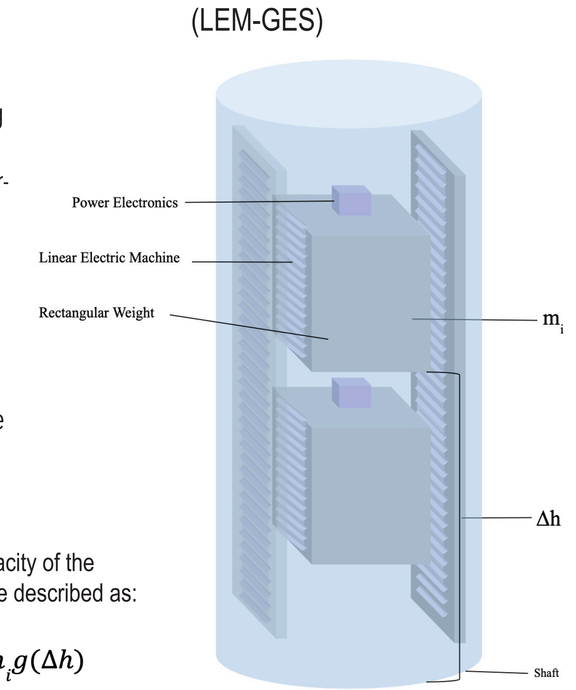


Figure 2 Linear Electric Machine Gravity Energy Storage System (LEM-GES)



- S-GES and LEM-GES involve the raising and lowering of a mass, typically concrete composite or steel, using a hoist or LEM to store energy.
- The mass is raised at times of energy abundance, storing potential energy while suspended, and released to fall back down when energy is needed, converting the stored potential energy into kinetic energy used to generate electricity through a turbine (hydro/air), or generator (free standing GES linear motor/rope piston).
- The use of an LEM increases the energy density of the container and can augment system lifetime and efficency.

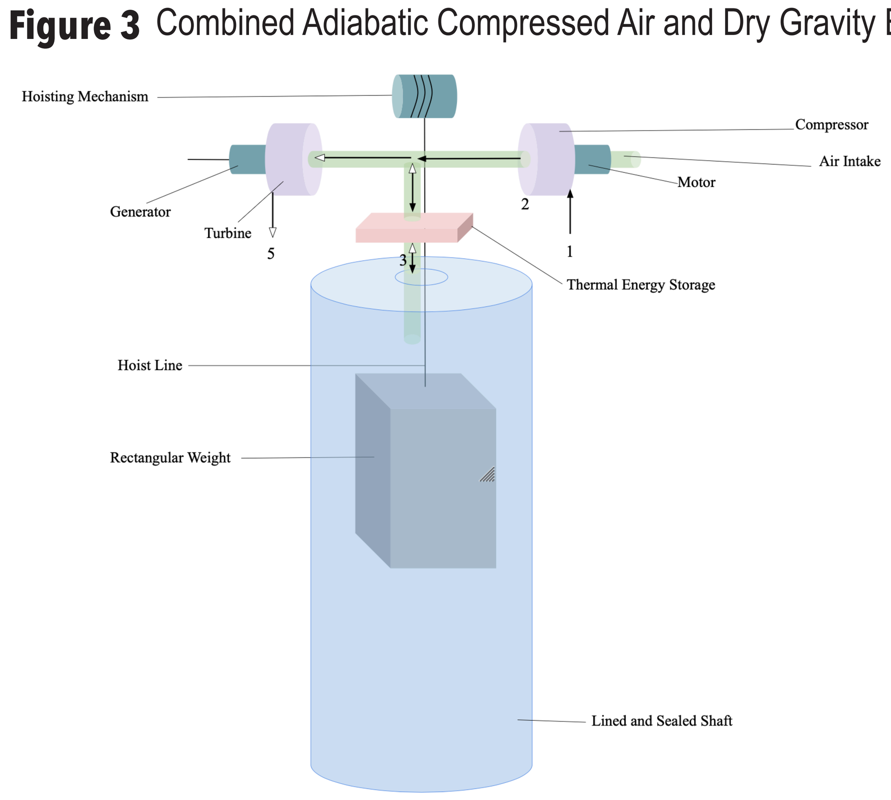
The energy storage capacity of the S-GES system can be described as:

$$E_{S-GES} = \eta l w \rho g \left(\frac{D}{2}\right)^2$$

The energy storage capacity of the LEM-GES system can be described as:

$$E_{LEM-GES} = \eta \sum_{i=1}^{N} m_i g(\Delta h)$$

Figure 3 Combined Adiabatic Compressed Air and Dry Gravity Energy Storage System (DCAES-GES)



- CAES systems power a motorized compressor with surplus electricity which intakes ambient air and pumps the air into a highly pressurized environment, such as a tank or cavern.
- When demand for electricity outpaces supply the compressed air is released through a turbine, expanded with heat in the process, and drives a generator to produce electricity. The pressurized environment has historically been abandoned salt mining caverns and abandoned oil and gas wells.
- In adiabatic systems the heat produced from the process of compression is stored via a thermal energy storage technology. During the generation phase this heat is used again to expand the escaping air, this process alleviates the need to burn fossil fuels for the purpose of expansion.

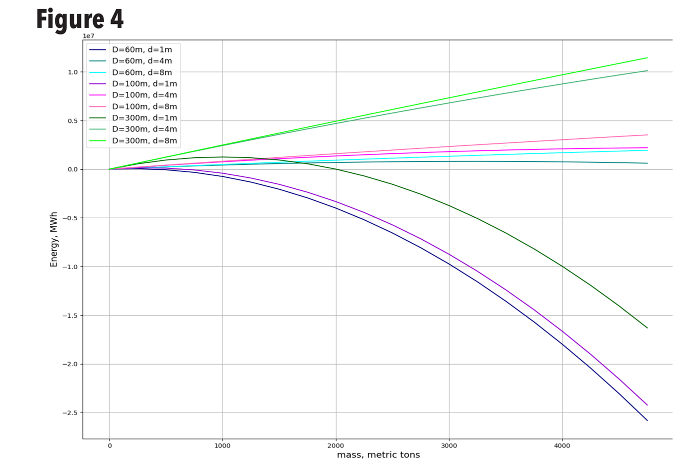
Utilizing one shaft for both forms of energy storage increases the energy and power density of the storage solution. When a combined DCAES-GES system is fully charged its energy capacity can be modeled as the summation of its constituent A-CAES and S-GES portions, affected by an overall system efficiency, as:

$$E_{DCAES-GES} = \eta_t (E_{A-CAES} + E_{S-GES})$$

$$E_{DCAES-GES} = \eta_t \left[\left(\frac{\gamma}{\gamma-1}\eta_{gen}\eta_m\eta_s\frac{T_{atm}}{T_{tes}}\frac{T_{tes}}{T_{sft}}f_t\right)p_{sft}V_{sft} + \eta l w \rho g\left(\frac{D}{2}\right)^2\right]$$

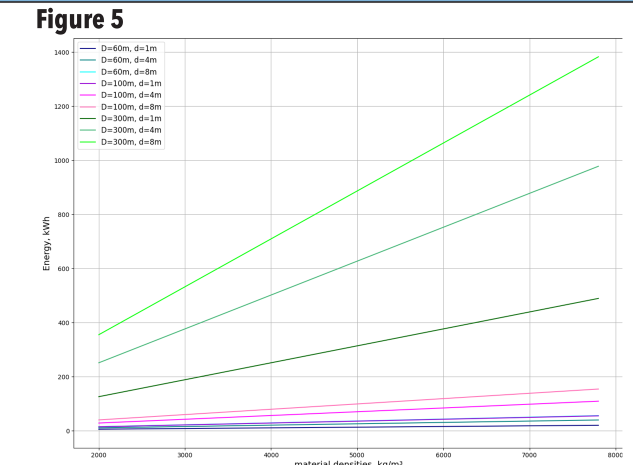
PARAMETER CONSIDERATION

Figure 4



Energy Storage Capacity of one material density at different shaft depths and weight dimensions for an S-GES system. For a given depth of mine shaft there is a maximum energy storage capacity related to the diameter of the mass chosen.

Figure 5



Energy storage capacity increases as material density increases for a weight shaped as a rectangular prism, and a given shaft depth and diameter. For reference, the material density of concrete is 2400 kg/m^3, of iron ore is 5150kg/m^3, and of steel is 7850kg/m^3.

CASE STUDY

COAL BED IDENTIFICATION

Extent of coal bed extraction through underground mining practices represented by black coloring, remaining coal in the seam represented by yellow. Figures constructed by use of GIS data available through the West Virginia Geologic and Economic Survey's Coal Bed Mapping Project.

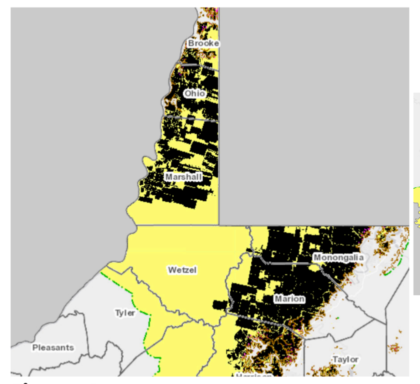


Figure 6

The Pittsburgh coal seam produced 45.5 million short tons through underground mining practices in 2021.

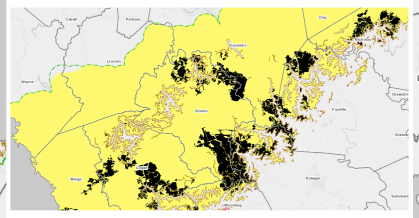


Figure 7

The Eagle coal seam produced 6.23 million short tons via underground practices in 2021.

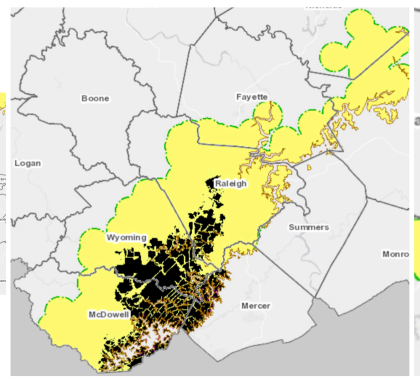


Figure 8

The Pocahontas coal seam produced 5.54 million short tons via underground practices in 2021.

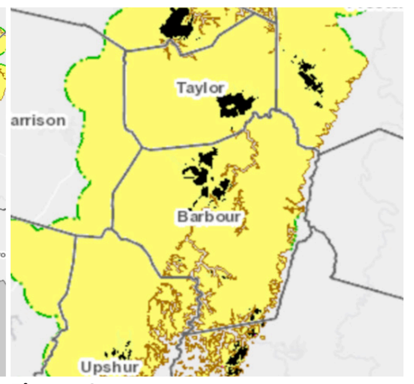


Figure 9

The Miiddle and Lower Kittanning coal seam produced 4.37 million short tons via underground practices in 2021.

MINE SHAFT IDENTIFICATION

- Through a combination of GIS data, state and federal permitting data, and extensive review of WV GES Mine Map Repository, 149 decommissioned or abandoned shafts and 33 active shafts were deemed suitable for modeling.
- Shafts of depths shallower than 200 ft or with diameters smaller than 8 ft were not included.
- It is assumed that all of the identified shafts are completely vertical with consistent radius, and that the surrounding earth has the structural integrity to support the hoisting equipment utilized.

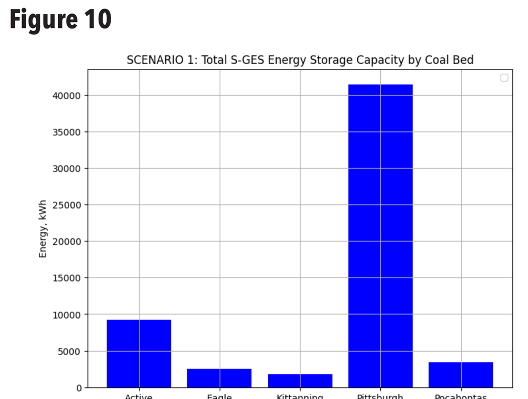
Table 2

Seam	Number of Shafts	Average Depth (ft)	Average Diameter (ft)	Number Lined
Pittsburgh	81	849	15.5	23
Eagle	24	419	10	12
Lower / Middle Kittanning	18	340	12	6
Pocahontas 3 / 6	26	485	19	0
Unknown Active	33	647	12.3	N/A

TECHNOLOGY APPLICATION SCENARIOS AND RESULTS

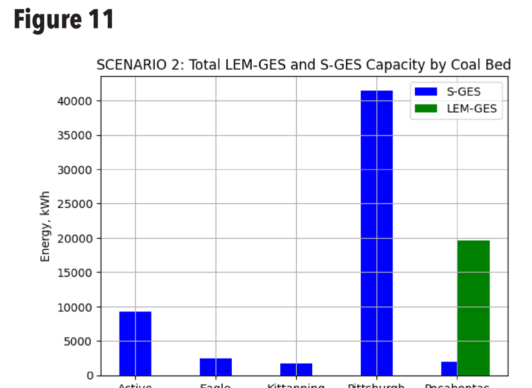
BASELINE SCENARIOS: S-GES, LEM-GES, DCAES-GES IN ALL VIABLE SHAFTS

Figure 10



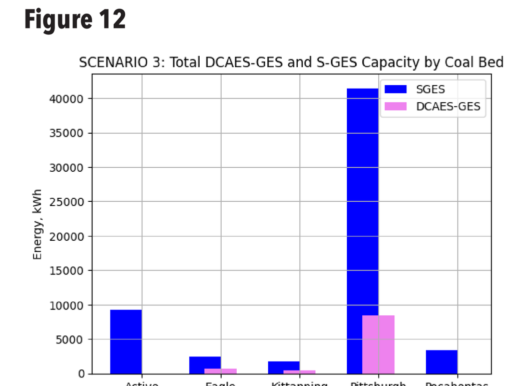
Applying S-GES systems to all identified mine shafts lends 54,915 kWh of energy storage capacity.

Figure 11



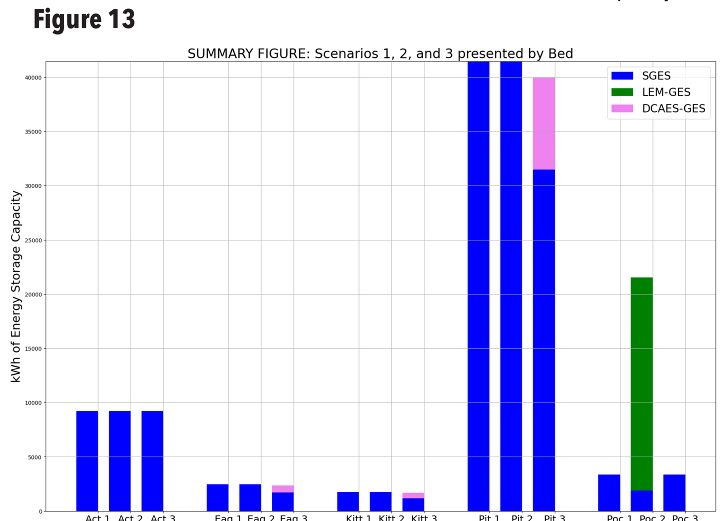
Applying LEM-GES, and S-GES systems to unflooded mine void volume lends 72,946 kWh of energy storage capacity.

Figure 12



Applying DCAES-GES, and S-GES systems to lined shafts lends 67,902 kWh of energy storage capacity.

Figure 13



- Scenarios one, two, and three reveal energy storage capacities of 55 MWh, 73 MWh, and 68 MWh respectively.
- The Pocahontas coal bed is identified as the most viable for implementation of LEM-GES due to extensive, un-flooded, mine void volume and the prevalance of high shaft density on a few permits.
- The Pittsburgh coal bed has been mined most heavily in the past decade and as such many of the shafts in the bed feature concrete or steel lining, making the bed a clear choice for DCAES-GES systems.

ANALYSIS

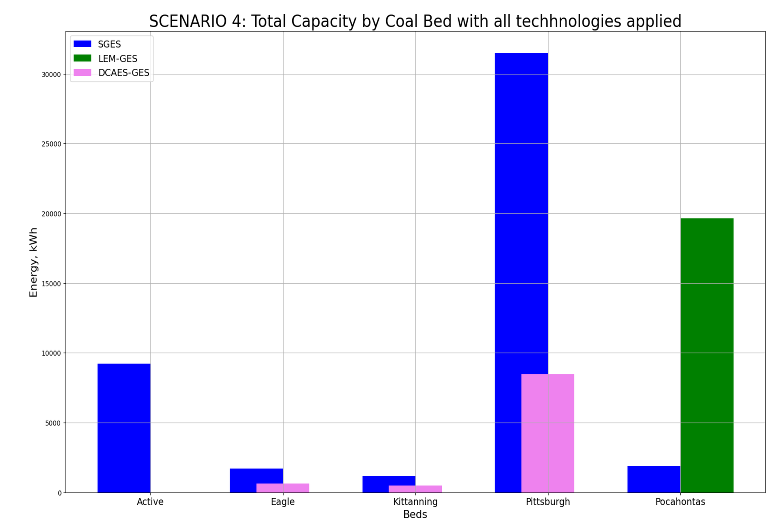


Figure 14

- Scenarios 1-3 identify the most effective coal bed to technology matches. Scenario 4 utilizes these matches to implement the best-suited technology in each identified shaft.
- Active shafts are paired with S-GES lending 9.2MWh of storage.
- The Eagle bed features 1.7MWh of S-GES and 643kWh of DCAES-GES.
- The Kittanning bed features 1.2MWh of S-GES and 496kWh of DCAES-GES.
- The Pittsburgh bed features 31.5MWh of S-GES and 8.5MWh of DCAES-GES.
- The Pocahontas bed features 1.9MWh of S-GES and 19.6 MWh of LEM-GES.

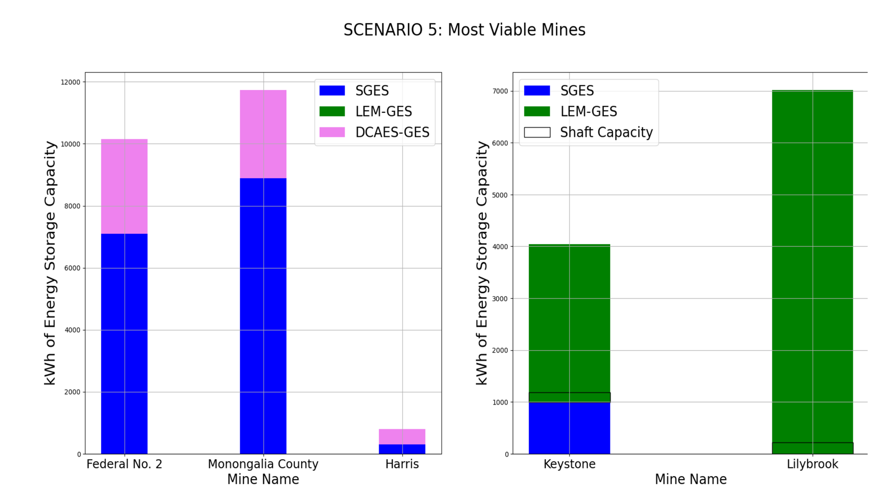


Figure 15

- Five of the reviewed mines stand out as locations for siting a gravity energy system due to the density of deep mine shafts located within one permit area. These mines are modeled above with the appropriate technology.
- While the maximum energy storage capacity of the LEM-GES system is large, the power factor of the system is affected by the maximum number of pistons able to be discharged at one time. A more helpful metric is the energy storage capacity of the shaft.
- For the Lilybrook and Keystone, while the energy storage capacities of the systems are 7 MWh and 4MWh, the storage capacity of the shafts are 215 kWh and 192 kWh.

LIMITATIONS

- The energy storage capacity figures reported in the case study are limited in accuracy by the quality of the collected data, the assumptions utilized in applying the technology models, and the reductionist nature of the energy capacity equations used.
- The total number of shafts identified is likely conservative due to the lack of reported shafts prior to 1990, and due to the illegibility of many reviewed mine maps.
- The analytical models do not consider charging and discharging time dynamics, and assume full efficiency of any renewable generation technologies utilized for charging the storage system.
- Future work could preform geotechnical analysis of mining lands to determine true feasablity.

DISCUSSION

The use of pre-sunk mine shafts decreases the overall investment costs of a gravity energy storage project. Construction, particularly excavation of a shaft, has been found to comprise 56% of the overall investment figure for a system of this kind. Using the shafts identified above not only diminishes, if not eliminates this cost, but also decreases construction time, and inflates future revenues. Decreasing the levelized cost of energy storage makes this project more attractive to potential investors by decreasing the payback period of a project. Additionally, the standalone investment tax credit (ITC) provided by the Inflation Reduction Act also de-risks investment in this kind of storage project.

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