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Assessing Compressed Air Energy Storage (CAES) Potential in Kentucky to Augment Energy Production from Renewable Resources

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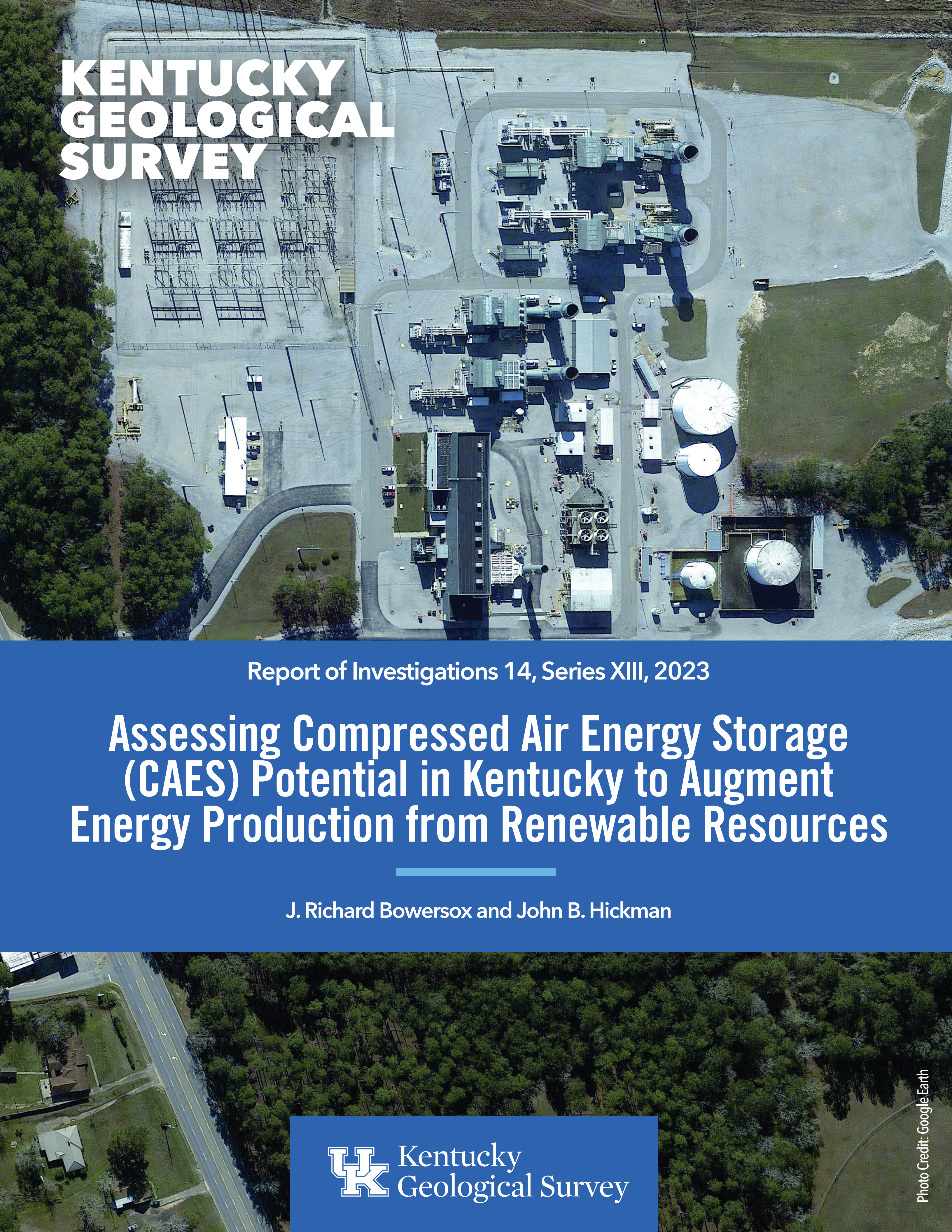
KENTUCKY GEOLOGICAL SURVEY



Report of Investigations 14, Series XIII, 2023

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Kentucky Geological Survey

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The background image depicts the PowerSouth Energy Cooperative CAES plant in McIntosh, Alabama, United States.

Kentucky Geological Survey
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Our Mission

The Kentucky Geological Survey is a state-supported research center and public resource within the University of Kentucky. Our mission is to support sustainable prosperity of the commonwealth, the vitality of its flagship university, and the welfare of its people We do this by conducting research and providing unbiased information about geologic resources, environmental issues, and natural hazards affecting Kentucky.

Technical Level

Statement of Benefit to Kentucky

This report describes several kinds of underground compressed air energy storage models which have the potential to become an economical low-carbon renewable energy resource, with a focus on those methods that work best in Kentucky.

Assessing Compressed Air Energy Storage (CAES) Potential in Kentucky to Augment Energy Production from Renewable Resources

J. Richard Bowersox, John B. Hickman

Abstract

Fossil fuel power plants in Kentucky have some of the highest emissions of greenhouse gasses in the United States. One potential strategy for mitigating greenhouse gasses from electric power generation is the co-installation of Compressed Air Energy Storage (CAES) and a renewable source such as photovoltaic solar electricity generation (PV solar generation). CAES with complementary co-installed PV solar generation enhances stand-alone PV solar generation because CAES power is available at night. CAES, however, requires both a site where large volumes of compressed air can be stored in the subsurface, and a heat source to prepare the stored air prior to entering the electricity-generating turbines. Co-installed PV solar electricity can provide the required thermal energy, but compressed air storage can be problematic. The two existing CAES plants, in Germany and Alabama, store compressed air in subsurface solution-mined salt caverns, however the thick salt deposits necessary to develop a compressed air storage cavern are not a part of Kentucky's geology. Six compressed air storage models were reviewed as part of this project: acid solution-mined caverns, abandoned limestone mines, advanced energy storage in mined air storage chambers, depleted gas fields aquifer storage; and cased wellbore energy storage. Each of these models has the potential for application in Kentucky. Two issues need to be addressed in applying CAES and its variations in Kentucky: ownership of the subsurface pore space where compressed air would be stored in depleted geologic reservoirs and aquifers, and social equity of the CAES electric power generation process. Pore space ownership is addressed under both state and federal law, generally from the standpoint of natural gas storage in depleted gas fields. These storage reservoirs would require an Environmental Protection Agency (EPA) injection permit. CAES models that do not impact porosity or groundwater may require other state and federal operational permits. Because CAES is both site-flexible and easily scalable, it provides a starting point for the conversation surrounding energy equity in the U.S. CAES with co-installed PV solar electricity generation provides a path to equitable power generation for all Americans.

Introduction and Previous Work

Fossil fuels, coal, and natural gas have historically served as Kentucky's principal sources of electrical power generation. Renewable resources comprise only a small part of Kentucky's energy mix through hydroelectric power (7 percent), biomass-electricity generation (0.6 percent), and photovoltaic solar power generation (0.2 percent) (U.S. Energy Information Agency, 2021a). This is changing. Recently, Louisville Gas and Electric Company (LG&E) and Kentucky Utilities installed a large-scale PV solar power generation facility, with a capacity of 10-MWs, at the E.W. Brown Generating Station in Mercer County, Kentucky (Louisville Courier-Journal, 2016). During daylight hours the PV solar panels generate and deliver DC electricity to charge batteries and cycle through electric power inverters into AC electricity that is fed into the grid. At night, the batteries serve as the primary energy source, discharging through the power inverters and converted to AC electricity that is then supplied to the grid. This process is well-tested and has been installed in sites around the world.

1.1 Compressed Air Energy Storage History

Compressed Air Energy Storage (CAES) is another efficient method of generating electricity during periods of peak demand during the day. The utility power generation-scale CAES process operates by storing high-pressure compressed air in a subsurface reservoir during periods of low demand, then tapping the stored compressed air during periods of high demand to drive an electricity-generating turbine. At the end of the day, the stored compressed air supply is replenished by injecting air back into the storage reservoir using surplus electricity to power a compressor (Kaiser and Krüger, 2019). The value of CAES as an adjunct to PV solar power generation was outlined by the U.S. Department of Energy—(2014), which highlighted the increased power quality and reliability in its service area, reduction of impacts associated with carbon emissions, and increased energy security through reduced fossil fuel consumption. This study focuses on the potential application of adiabatic and/or diabetic CAES in Kentucky and its regional siting options to augment renewable resources, particularly co-installed PV solar power generation. Two CAES systems may be implemented for a utility-scale power plant: the diabatic system and the adiabatic system. According to the definition provided by Quincy Compressor, "In an adiabatic energy storage system, the heat produced during the air compression process is kept and then released into the air during the decompression of the stored air. Instead of storing the heat during the compression process, a diabatic storage system uses intercoolers to dissipate the heat into the air as a waste product." (Quincy Compressor, 2022). The two existing CAES plants use constant volume compressed air storage where the compressed air is stored in salt dome caverns geologic reservoirs. Compressed air can also be stored in constant-pressure reservoirs where the air pressure is maintained but the reservoir volume changes as air is withdrawn or added. Two new power plants, discussed below, will use this technology.

1.2 CAES Becomes a Competitive Electric Power Source

CAES is a long-proven but underutilized technology. There are currently two commercial power plants in service in Germany and Alabama and a demonstration

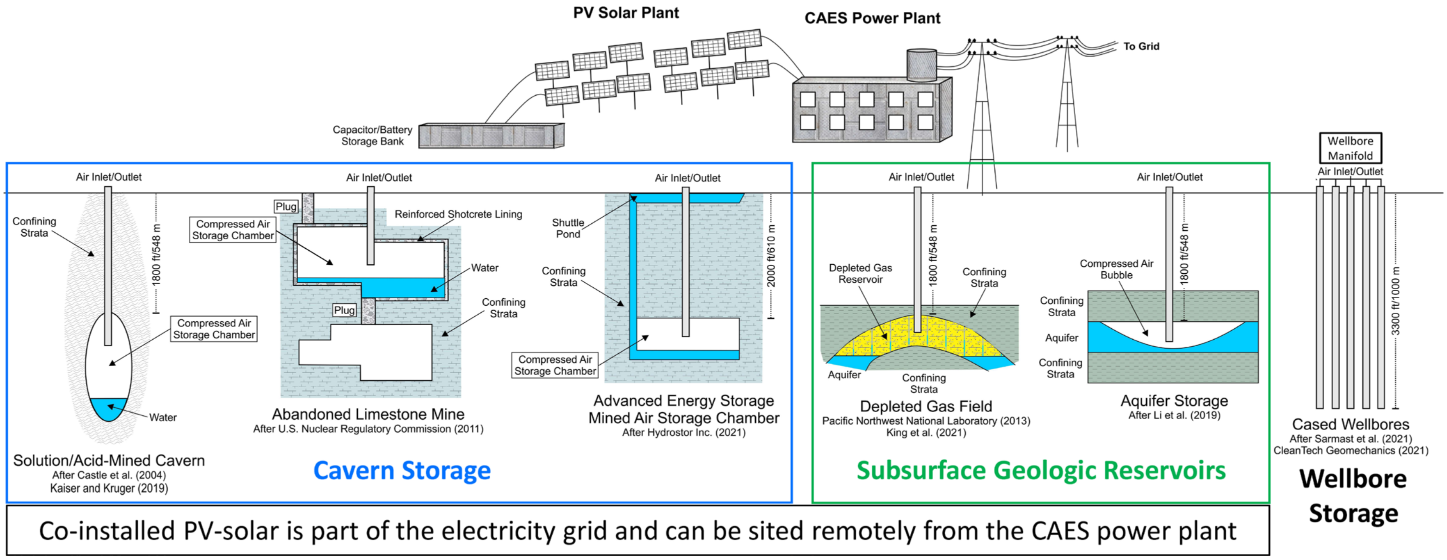
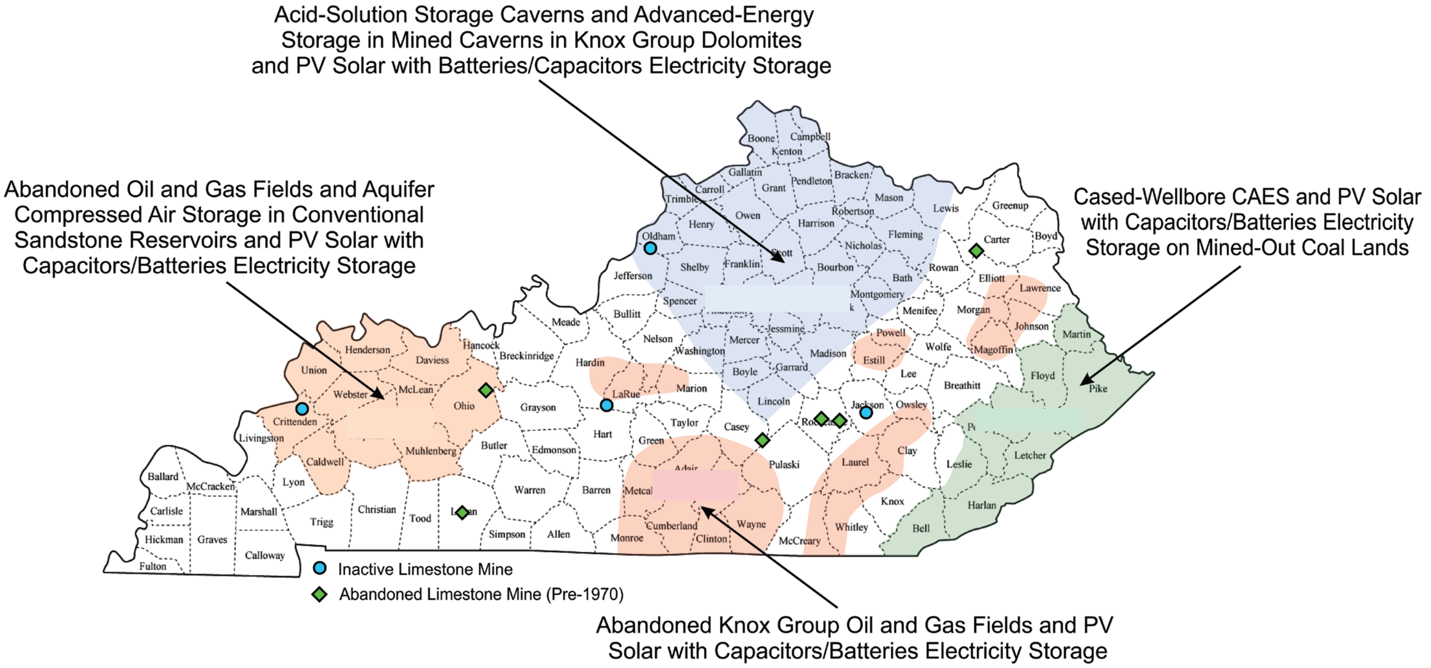


Figure 1. Compressed Air Energy Storage models discussed in this report. Solution-mined caverns in thick salt beds provided the energy storage for the two existing CAES power plants. Additional compressed air storage options have been advanced, however, only an Advanced Energy Storage CAES power plant (A-CAES) is currently under construction.

CAES power plant in Canada (Hydrostor Inc., 2019). The two commercial CAES power plants are a 290-MW plant at Huntorf, Germany built in 1978 (Pacific Northwest National Laboratory, 2013; IRENA, 2017) and the PowerSouth Energy Cooperative McIntosh, Alabama (PowerSouth), 110 MW CAES plant built in 1991 (Pacific Northwest National Laboratory, 2013; IRENA, 2017). Both the Huntorf and PowerSouth plants use the diabatic process for electricity generation. Diabatic CAES requires natural gas fuel to heat the expanding air to drive the generation turbine (Lamboo, 2020). Both the Huntorf and PowerSouth plants store air underground in solution-mined salt caverns (Fig.1). Three additional CAES projects in the United States were planned in New York, California, and the Pacific Northwest, but ultimately were abandoned because of a lack of funding. The first was a 150-MW CAES project in an abandoned salt mine at Reading, New York which was discontinued after the completion of Phase 1 engineering and financial evaluations (National Energy Technology Laboratory, 2010). Pacific Northwest National Laboratory (PNNL) also identified three suitable sites for CAES in porous and permeable rock structures in the Pacific Northwest, but they never progressed beyond economic modeling (Pacific Northwest National Laboratory, 2013). Likewise, Pacific Gas and Electric (PG&E) identified a suitable site for CAES in a depleted gas field in central California with the plan of building a facility capable of producing 300 MW per 10 hours (Medeiros and others, 2018a), but abandoned the project when it was evaluated as being non-commercial.

A-CAES became a competitive electric power generation source in 2015 when Hydrostor, a Canadian company, completed construction and opened the first commercial CAES plant since 1991. Hydrostor built two concept-demonstration advanced CAES design (A-CAES) pilot plants in Ontario, Canada: the Toronto Island plant in 2015 and the 1.75 MW 6-hour Goderich plant in 2019 (Inside Climate News, 2021). The Hydrostor (2021) A-CAES power generation cycle system works by converting excess grid energy into compressed air. This compressed air is sent into purpose-built underground caverns, where it displaces water to create storage capacity (in other words, stored energy in the form of pressurized air). This compressed air can then be discharged through an air turbine to generate electricity, with no additional fuels, when needed in the grid.

These plants, the first adiabatic CAES plants to be placed online, also demonstrated hydrostatically-compensated CAES power generation, a process that maintains a constant air pressure in a compressed air storage chamber using a water column connected to a surface storage reservoir (Inside Climate News, 2021). Hydrostor is completing the feasibility-stage development of a 200-MW, utility-scale A-CAES plant at Broken Hill, New South Wales, Australia. They are also in the process of permitting two A-CAES


Acid-Solution Storage Caverns and Advanced-Energy Storage in Mined Caverns in Knox Group Dolomites and PV Solar with Batteries/Capacitors Electricity Storage

Abandoned Oil and Gas Fields and Aquifer Compressed Air Storage in Conventional Sandstone Reservoirs and PV Solar with Capacitors/Batteries Electricity Storage

Cased-Wellbore CAES and PV Solar with Capacitors/Batteries Electricity Storage on Mined-Out Coal Lands

● Inactive Limestone Mine

◆ Abandoned Limestone Mine (Pre-1970)

Abandoned Knox Group Oil and Gas Fields and PV Solar with Capacitors/Batteries Electricity Storage

Figure 2. This evaluation reviewed both CAES models (Figures 3–9) and Kentucky geology to determine optimal areas for the construction of CAES power plants. Assuming co-installation of PV Solar electric power generation with CAES, and power grid access available to both kinds of power generation plants, areas in Kentucky where the CAES models were most compatible were assigned with the geology. cased-wellbore CAES/cased-wellbore Advanced CAES are shown as being best suited to mined-out coal lands in eastern Kentucky, however these CAES models are independent of local geology and could be installed anywhere in the Commonwealth where suitable tracts of land were available.

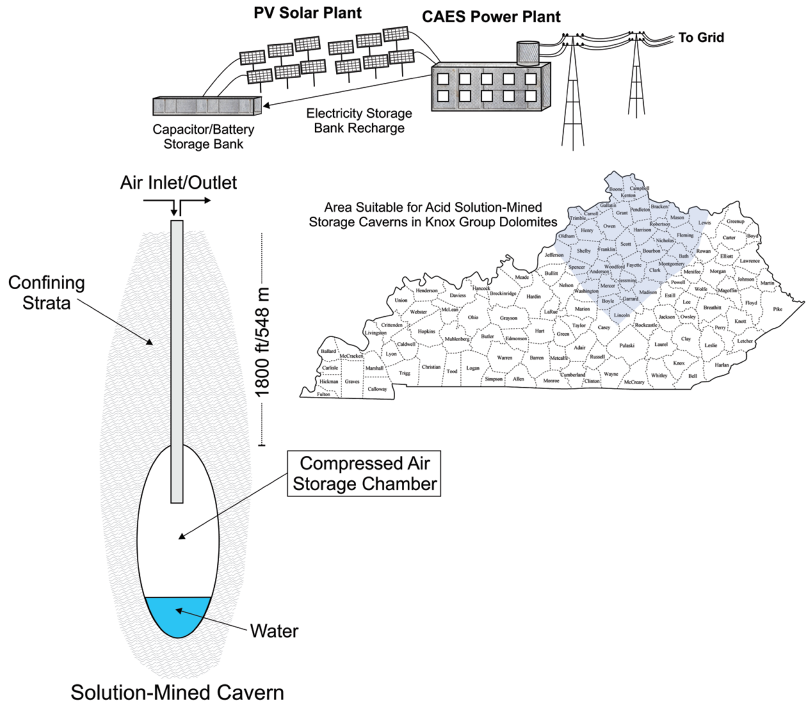
plants with the California Energy Commission, including a 500-MW plant in San Luis Obispo County, California (California Energy Commission, 2021a), and a 400-MW plant in Kern County, California (California Energy Commission, 2021b).

2. Geological Siting Criteria in Kentucky

The primary factor in siting a CAES power plant is a suitable compressed air storage reservoir or chamber of sufficient capacity to service the power plant. Placing a CAES storage reservoir in a shallow subsurface such as a converted limestone mine will require sealing the interior surfaces to prevent air leaks once under pressure. A storage reservoir in a porous and permeable strata in the deeper subsurface, much like a subsurface CO_2 storage project (e.g. Bowersox and others, 2019), requires a geologic structure capped by impermeable strata of sufficient geomechanical strength to contain the injected air without developing fractures and allowing migration of the injected air and any reservoir fluids to freshwater aquifers or the surface (see the discussions in Bowersox, 2013; Bowersox and others 2019; Bowersox and others, 2021). The subsurface compressed-air reservoir pressure must be less than the fracture pressure, the pressure at which overlying strata will fracture, at the reservoir depth (i.e., subsurface fracture gradient times reservoir depth). As illustrated in Figure 7, the fracture gradient in Kentucky is typically about 0.60 psi/ft of drilled depth (13.6 MPa per km; e.g. Bowersox and others, 2021), thus a subsurface compressed-air storage reservoir capable of storing air at 1,100 psi. The PowerSouth power plants proposed and under construction provide models for this type of storage reservoir, which requires a depth greater than 1,833 ft and capping by impermeable strata to ensure compressed air confinement in the reservoir. Kentucky geology provides a variety of settings suitable for CAES energy development (Fig.2) including acid-mined solution caverns in the Knox Group dolomites (Fig. 3), abandoned limestone mines (Fig.4), abandoned oil and gas reservoirs and aquifer storage in porous and permeable sandstones and carbonate rocks (Fig.5), advanced CAES in mined caverns (Fig.6), and cased-wellbore CAES (Fig.7) and advanced cased-wellbore CAES (Figs. 8 and 9). PV solar power generation is compatible with each of these CAES processes. Site screening in this study has identified that abandoned limestone mines and abandoned oil and gas fields may be the most immediately feasible geologic CAES air storage sites in Kentucky, whereas cased-wellbore CAES and advanced cased-wellbore CAES are the most flexibly sited CAES processes.

2.1 Solution-Mined Caverns

Both existing utility-scale CAES power plants use solution-mined salt caverns for compressed air storage (Fig. 3). The 290-MW Huntorf, Germany, CAES power plant, completed in 1978, has a



After Castle et al. (2004), Kaiser and Kruger (2019)

Figure 3. Acid-mined CAES storage caverns and, and conventionally underground-mined Advanced-CAES (Figure 6), will require thick sections of impermeable carbonate rocks at depths of about 1500–2000 ft for their construction (see Castle et al., 2004). These models of CAES storage would be best suited for Knox Group dolomites in the subsurface of north-central Kentucky.

5.3-million cubic ft compressed air storage cavern at depths of 1,970-2,625 ft and operating at 1,015 psi (Bine Informationsdienst, 2007 [German]; converted from metric units). The 110-MW PowerSouth CAES plant, completed in 1991, stores 19 million cu ft of compressed air in a cavern about 200 ft in diameter and 1,000 ft high (PowerSouth Energy Cooperative, 2015) at depths of 1,475-2,460 ft, operating at 1,100 psi (Bine Informationsdienst, 2007 [German], converted from metric units (PowerSouth Energy Cooperative, 2015). Thick salt beds and salt domes, however, are not a part of Kentucky's subsurface geology. The alternative to solution-mined salt caverns is acid-solution caverns in carbonate rocks (Castle and others, 2004). Between 1973 and 1992 E.I. du Pont de Nemours (DuPont) unintentionally created acid-solution caverns in its number 1 and number 2 Waste Acid Disposal wells at its Louisville manufacturing plant (1 WAD and 2 WAD; KGS Record Numbers 11169 and 11170, kgs.uky.edu/kygeode/services/oilgas/). Waste hydrochloric acid averaging 6 weight-percent hydrochloric acid had been injected into the Copper Ridge Dolomite of the Knox Group below 3,000 ft, at wellhead pressures less than 50 psi and injection rates less than 100 GAM (Clark and others, 2005). By 1990 advanced sonar caliper measurements in the DuPont 1 WAD well found a cavern about 450 ft wide and more than 40 ft high, although the entire height of the cavern could not be measured because of the presence of CO_2-rich fluid phase in the cavern (Clark and others, 2005). Advanced sonar caliper measurements in the DuPont 2 WAD well showed that the acid had created an irregular solution cavern about 250 ft wide and about 50 ft high (Clark and others, 2005). Castle and others (2004) investigated creating acid-solution gas-storage caverns in carbonate rocks in Kentucky, Ohio, Indiana, West Virginia, Pennsylvania, and New York. Their screening model required depths more than 4,000 ft, and optimally more than 6,000 ft, to be able to store up to 2 billion cubic ft of gas. With this pressure criteria, the estimated gas storage reservoir pressure would be between 2,200 psi and 3,300 psi. Castle and others (2004) assumed that the gas storage cavern would be created by hydraulic fracturing limestone and pumping hydrochloric acid into either a single wellbore or two wellbores adjacent wellbores. The process uses a single wellbore for pumping fresh hydrochloric acid into the rock and spent acid out of the wellbore, creating a vertical elliptical cavern, or using two adjacent wellbores with one wellbore for pumping fresh acid into the rock and the second to pump spent acid out of the rock, creating a horizontal dog bone-shaped cavern (Castle and others, 2004). Costs to construct and equip a gas storage cavern in limestone with a capacity of 0.5B1 BCF of gas were estimated to be about $3.3 million in 2004 (about $4.8 million in 2021). The group also estimated that costs to create the same gas storage cavern in dolomite would be about six percent more than one in limestone (Castle and others, 2004).

2.2 Abandoned Limestone and Coal Mines

Inactive and abandoned limestone mines (Fig.4) could be repurposed and converted to compressed air storage caverns at relatively low costs (U.S. Nuclear Regulatory Commission, 2011). In addition to a geotechnical assessment of the integrity of the caverns, the mine conversion process should include clearing dust and debris and plugging any unneeded entrances or tunnels with concrete to prevent air leakage (Menéndez and others, 2019). The integrity of the storage cavern tunnels could be maintained by lining tunnels with 5 cm (2 in) or more of reinforced shotcrete (or comparable gunite) or a high-strength of glass-fiber membrane (Menéndez and others, 2019).

During this project, we identified four inactive limestone mines (Kentucky Transportation Cabinet, 2020) and six abandoned limestone mines (Dever and Weisenfluh, 2013) as possible CAES sites (Fig. 4; see also Appendix 1). Operationally, abandoned coal mines may safely store compressed air if the shafts and drifts are completely sealed from remaining coal seams to mitigate risks of tunnel wall leaks and ceilings collapse and prevent contact of hot compressed air with any unsealed coal seams to avoid combustion of the coal (Lutynski, 2017; Menéndez and others, 2019). Considering this, along with questions of access, drift and shaft stability, water incursion, coal dust, and methane emissions, abandoned coal mines were not evaluated further.

2.30 Depleted Oil and Gas Fields

In their proposal to construct a CAES plant in the depleted King Island gas field in San Joaquin County, California, PG&E considered ten geological factors in determining the suitability of the site: reservoir size, porosity, permeability, depth and reservoir pressure, reservoir thickness, remaining gas reserves, reservoir trapping mechanism, number of producing intervals, reservoir drive mechanism, and geological complexity (Medeiros and others, 2018a; Medeiros and others, 2018b). For planning purposes, Pacific Northwest Laboratory (2013) provided a shorter list of minimum reservoir criteria: 1500 ft depth, 30 ft reservoir thickness, 500 mD permeability, 10 percent effective porosity, 100 ft of overlying low-permeability confining strata, and an anticlinal structure.

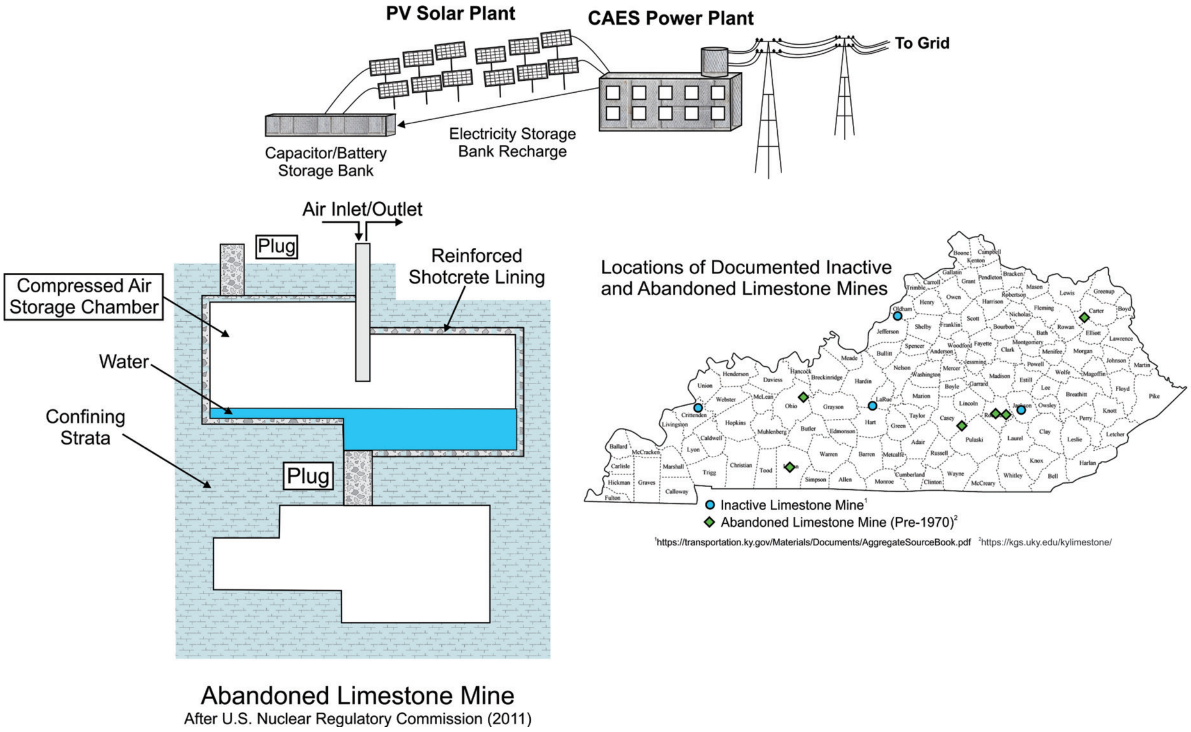


Figure 4. Locations of four inactive and six abandoned limestone mines in Kentucky that may be suitable for repurposing as CAES with PV solar power plants. (Kentucky Transportation Cabinet, 2020; Limestone and Dolomite Resources of Kentucky, 2020). Older limestone mines (pre-1970) have been tabulated, but not shown because their current statuses are unknown.

Using these criteria as a guideline, our team searched the Kentucky Geological Survey (KGS) oil and gas well database (kgs.uky.edu/kygeode/services/oilgas/) for matching sites in the Illinois Basin region of western Kentucky. This region was chosen because of the many Mississippian sands in the geologic section found at depths between 1,800 ft and about 3,000 ft that had been cored (Figs. 2 and 5) during oil and gas development. Reviews of wells matching CAES constraints found an eight-county area around Henderson County identified abandoned oil and gas fields potentially suitable for CAES. Our subsequent laboratory research focused on measuring the permeability of cores from the Mississippian Tar Springs, Cypress, Bethel, Hardinsburg, and Benoist sands and Aux Vases Limestone to determine their suitability as CAES storage reservoirs. There were 362 permeability measurements made by student aide Kyle Skeese in 17 cores from the KGS Earth Analysis Research Library (EARL) collection in the 10-county area of interest shown in Figure 5. Permeability measurements made using the Core Lab PPP-250 portable permeameter purchased for this project, found few permeabilities of more than 500 mD (Appendix 2). Research on the effects of injected air on the mineralogical composition of a storage reservoir is not available beyond the findings obtained from a single core plug from PG&E's proposed CAES storage site in the King Island gas field (Jacobson James and Associates, 2020). Although no analytical results were released, Jacobson James and Associates (2020) found that during air injection carbon dioxide was generated from carbonate in the core plug while the pH of produced water was decreased, and mainly of iron oxide phases including magnetite and goethite were deposited in the pores. Their interpretation was that pyrite and siderite were oxidized to iron oxide and sulfuric acid, and carbon dioxide and heat were generated (Jacobson James and Associates, 2020). Jacobson James and Associates (2020) provided recommendations regarding further research and testing needed to manage oxygen depletion and corrosivity effects including heat flow modeling and monitoring, and reservoir development and operating procedures. They concluded, however, that significant porosity and permeability changes were not expected to occur. Thus, beyond the dissolution of carbonate in the reservoir rock, it appears unlikely that the injection of air into sandstone would cause major operational issues. Comparable analyses and flow tests of cores from a potential compressed air storage reservoirs in Kentucky, would be required before committing to a CAES project developed in abandoned oil and gas reservoirs. The Trapp gas field in Clark County (Humphreys and Watson, 1996) might be suitable for compressed air storage in the St. Peter Sandstone, although the very low permeability, averaging 14.1 mD (Humphreys and Watson, 1996, table Osp-2), and shallow depth to the top of the reservoir at 1,598 ft (Humphreys and Watson, 1996, table Osp-1) would limit the compressed air charge-discharge rate and pressure.

2.31 Aquifer Air Storage

Compressed air storage in aquifers (Fig. 5) creates a high-pressure air bubble in horizontal porous and permeable strata below impermeable confining strata (Li and others, 2019; Wang and Bauer, 2017). As such, it will have the same storage reservoir requirements and limitations as compressed air storage in abandoned oil and gas fields (above). Although structurally closed anticlines would be the first choice for compressed air storage, flat-lying aquifers are more likely to be available (Jarvis, 2015; Guo and others, 2016; Wang and Bauer, 2017). Jarvis (2015) constructed 2D aquifer storage injection/production models for three horizontal reservoirs scenarios in TOUGH2 modeling software where aquifer pressure was maintained at 46- 66 bar (667-957 psi) at depths of 575-650 m (1,186-2,133 ft). Jarvis's (2015) 3D model showed that cycling air in the reservoir for a year yields no water and provides a cycle efficiency of about 80 percent without reducing efficient aquifer pressure.

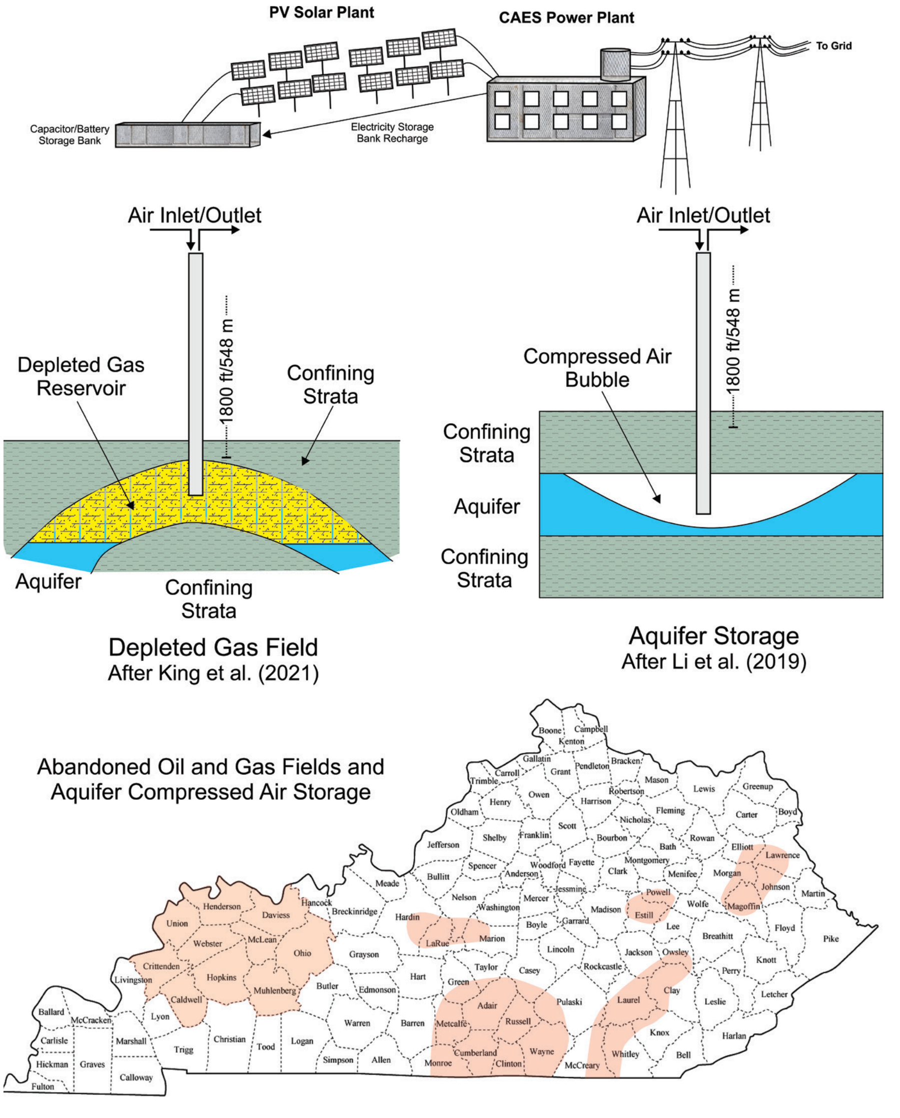


Figure 5. Areas identified as suitable for compressed air storage in depleted gas and oil fields and aquifer storage. Areas with abandoned oil and gas fields in sandstones, also with potential for aquifer storage, are colored orange and areas with abandoned oil and gas fields in Knox dolomites are shaded.

2.32 Abandoned Gas Storage Fields

Storing compressed air in abandoned Kentucky gas storage fields is not feasible. Considering an average subsurface fracture gradient in Kentucky of about 0.60 pounds per square in per ft of depth (i.e., Bowersox and others, 2021), reservoirs in the range of 1,800-3,000 ft depth would be required meet U.S. Environmental Protection Agency (EPA) storage reservoir integrity requirements for a compressed air storage reservoir pressure of 1100 pounds per square in or more (U.S. Environmental Protection Agency, 1994). Locations of the active natural gas storage fields in Kentucky are national security sensitive information and generally not released to the public (Kentucky Public Service Commission, 2008). Locations of many of the gas storage fields in Kentucky, however, can be found the Kentucky public service commission website. Five gas storage fields are listed as abandoned (https:\\psc.ky.gov). The five known abandoned gas storage fields lie at an average depth of 884 ft, too shallow to meet EPA subsurface injection regulations for high-pressure gas injection.

2.4 Advanced Energy Storage CAES (A-CAES)

A model with potential applicability in Kentucky, the A-CAES model developed by Hydrostor Inc. of Toronto, Ontario, Canada, involves the storage of compressed air in a deep, mined cavern and maintenance of that air pressure by a water cushion hydraulically tied to the surface. Hydrostor's A-CAES technology uses electricity from the grid to run an air compressor, producing heated compressed air. The heat is extracted from the air stream and stored for later use on discharge. The cooled compressed air is then sent underground and stored in a cavern, which can be either pre-existing or purpose-built to suit system requirements. When the grid requires dispatchable energy capacity, the air is brought back to the surface, re-collects the stored heat, and is expanded through an air turbine to generate power on demand (http://www.hydrostor.ca/projects). This model was successfully tested in 2021 at the Goderich A-CAES Facility, Goderich, Ontario, Canada (Hydrostor Inc, 2019). The Goderich A-CAES Facility is rated at 1.75 MW of peak power output, has a 2.2-MW charge rating, and an energy storage capacity of more than 10 MW-hours (Hydrostor Inc, 2019). Hydrostor presently has an A-CAES plant under construction in Broken Hill, New South Wales, Australia, and is permitting the construction of two comparable A-CAES plants in California (California Energy Commission, 2021a, 2021b).

The project description, taken from Section 2 of the Application for Certification (AFC) summarizes the discussion of the proposed Pecho Energy Storage Center in San Luis Obispo County, California (California Energy Commission, 2021a). The AFC describes that compressed air will be stored in a mined 630,000 cubic yards storage cavern 2,000 ft below the surface where air pressure will be maintained at 870 pounds per square in (freshwater hydrostatic gradient of 0.435 pounds per square in/ftat 2000 ft = 870 pounds per square in cavern pressure) (California Energy Commission, 2021a). The document also describes that air pressure in the storage cavern will be hydrostatically compensated by a 2,000-ft water column tied to a 500-acre-reservoir through an 8-ft diameter water conduit to maintain storage reservoir pressure (Fig. 6) (California Energy Commission, 2021a). The plan outlines that the air-storage cavern will be lined with shotcrete for geomechanical stability and large fractures grouted to reduce groundwater inflow to the cavern (California Energy Commission, 2021a). The Pecho Energy Storage Center maximum designed water flow rate is 18 ft per second (about 900 cubic ft of water per second, or about 75 acre-feet of water per hour) and compressed air will be charged and discharged through a 4-diameter stainless steel liner sized to limit airflow to a maximum of 110 ft per minute (about 1380 cubic ft of compressed air per minute)and placed in the mined air shaft and positioned at the high point of the storage cavern roof to ensure it is not submerged during operation (California Energy Commission, 2021a).

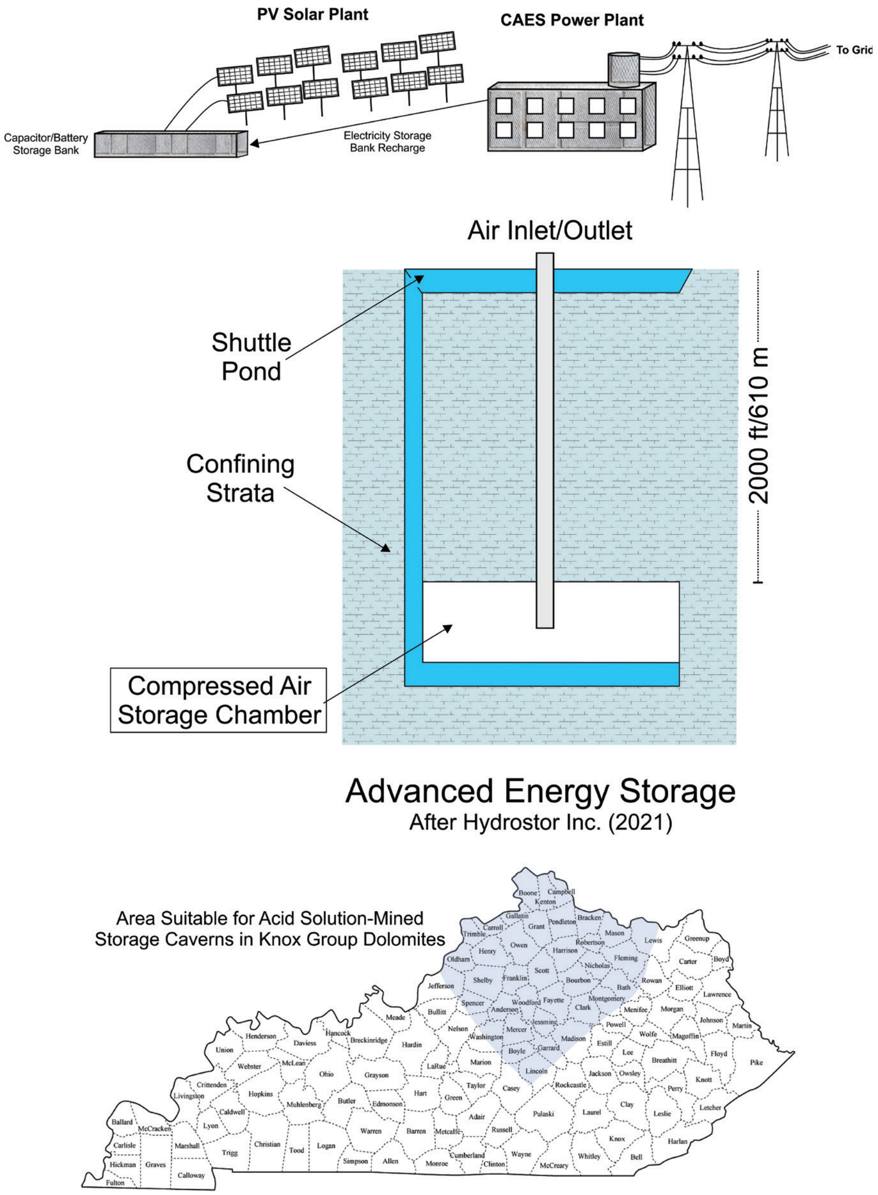


Figure 6. Schematic diagram of the advanced energy storage CAES model of Hydrostor Inc. currently in the permitting process in California (Farrell, 2021). Compressed air is stored in a 630,000 cubic yards cavern excavated 2000 ft below the surface and pressure is maintained at 870 psi by a water cushion in the storage chamber with a water column connected to a 500 acre-ft surface shuttle pond (https://www.energy.ca.gov/powerplant/caes/pecho-energy-storage-center).

The Pecho Energy Storage Center is designed to deliver 400 MW of carbon-free electricity for up to 14 hours and deliver 3200 MW-hours over an eight-hour period when operating at name-plate capacity. (California Energy Commission, 2021a). The construction cost of the Pecho Energy Storage Center is estimated at $800 million, providing 200-450 skilled-labor jobs during the estimated 4-years of construction, and 3040 good-paying jobs once in operation (Ferrell, 2021). On January 10, 2021, the company announced that Goldman Sachs agreed to a $250 million private

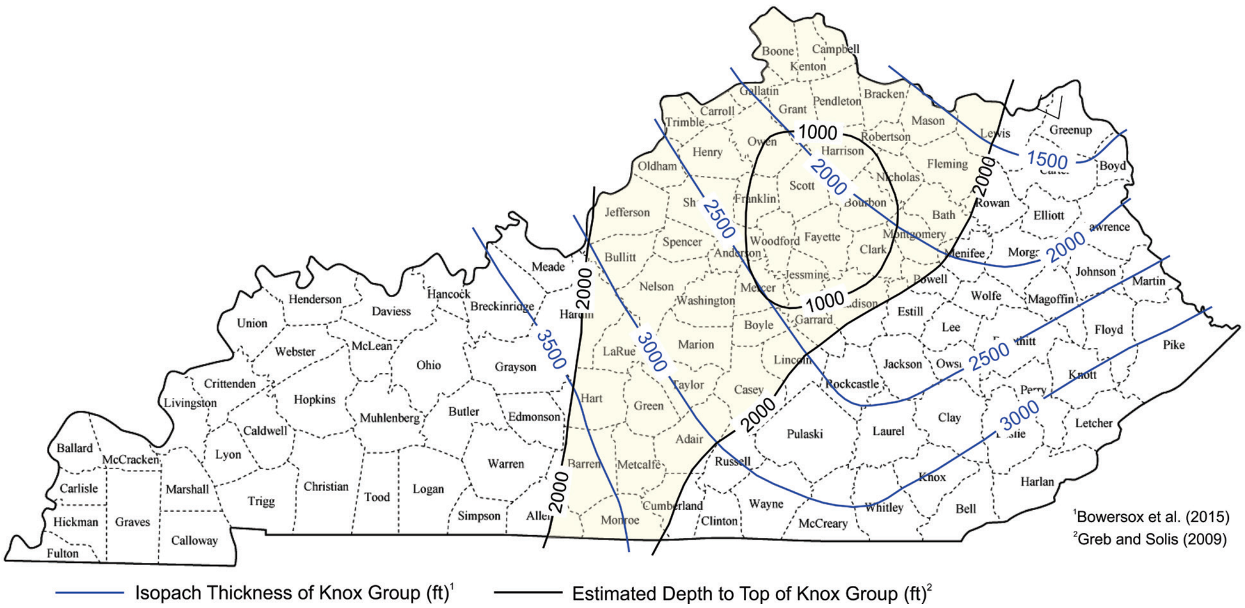


Figure 7. Isopach thickness and depth to top of the Knox Group in central Kentucky. The shaded area, where the top of the Knox is ~1500 ft to >3500 ft thick (modified from Bowersox et al, 2015) and has the potential for mining compressed air storage caverns at depths below 2000 ft (depths from the surface elevation to structural contours; modified from Greb and Solis, 2009).

equity investment in Hydrostor as growth capital, a move that demonstrates the rise in interest in these types of energy development projects (Spector, 2022).

Hydrostor's A-CAES model may have potential for development in abandoned limestone mines in Kentucky. The most critical issue would be the depth requirements, illustrated in Figure 4. Limestone caverns in Kentucky could possibly be mined to 2,000 ft on the Lexington Dome in north-central Kentucky where the Knox Group is shallower than 2,000 ft below the surface and 1,500-3,500 ft thick (Fig. 7). The Knox is thick enough in this region that a compressed-air storage cavern could be mined at a depth 2,000 ft below the surface and have a volume sufficient to serve an A-CAES power plant comparable to Hydrostor's. Siting an A-CAES cavern would require drilling geotechnical boreholes to determine rock properties, faults and fractures, water influx, any oil or gas present in the section to be mined, and the presence of hydrogen sulfide gas. Some of this information may be gleaned from KGS online well records (the KGS oil and gas well database; https://kgs.uky.edu/kygeode/services/oilgas/)and from cores and cuttings in the KGS Earth Analysis Research Library (EARL) collections (https://www.uky.edu/KGS/EARL/), but site-specific information would require drilling and coring new appraisal wells into the prospective compressed air storage geologic section.

2.5 Cased-wellbore CAES (CW-CAES)

Cased-wellbore CAES has been advanced as a model that improves the round-trip efficiency of the CAES system by storing energy as both compressed air and thermal energy in cased wellbores (Sarmast and others, 2021; US Patent 2021/0024290A1). This energy storage model is independent of local geology and has modular scalability, as the number of compressed air storage wellbores can be adjusted to generate the required electricity (Fig.8). Sarmast and others (2021) modeled a partial-adiabatic 19 MW-hour project where compressed is stored at 6 MPa's (870 pounds per square in) and 200 degrees Celsius (392 degrees Fahrenheit) in 68 10-meter-deep storage wells. They found round-trip efficiency to be 40 percent, which is higher than comparable diabatic projects operating under the same conditions (Sarmast and others, 2021). However, the modeled project might be difficult to implement as it relies on a design including storage wells spaced at 1 m apart. Practically, it will be difficult to drill and complete wells with this spacing and difficult to service them during operational upsets. CleanTech Geomechanics Inc. (2021) revised the Sarmast and others (2021) model by proposing deeper wellbores, 500-1,500 ms deep (1,640-4,920 ft deep), increasing air storage pressure to 50 MPas (7,250 pounds per square in), and keeping the compressed air temperature at 200 degrees Celsius (392 degrees Fahrenheit). Under these conditions, more than 10 MW-hours of energy could be stored in a 30 centim (10-in) cased wellbores providing a storage volume of 7 cubic ms per 100 ms of depth (247 cubic ft per about 330 ft of depth), or a volume of compressed air in four wellbores sufficient to generate 40-60 MW-hours (CleanTech Geomechanics Inc., 2021). This model would require high-strength/high-temperature wellbore casing comparable to API N80, 73.2 pounds per ft casing (U.S. Steel Tubular Products, 2014).

3. Discussion

This study discusses seven different CAES models (Fig. 1), all of which are compatible with co-installed PV solar energy and require only a site and access to the electricity grid to be constructed and operable. While this study, which focuses on CAES and renewal resources excludes biomass as an electric power generation model of because of its greenhouse gas emissions, the renewable resource to be augmented by CAES in Kentucky is PV solar electricity generation (see Chen and others, 2018). Electricity generated by PV Solar is daytime only, so electricity must be stored for delivery at night. Although batteries are the usual storage solution for nighttime electricity deliveries, capacitors can be scaled for bulk electricity storage as backup for PV solar with potential storage costs less than $0.05 per Kwh (Miller,2010). Only one CAES model, solution-mined storage caverns (Fig. 3), is in commercial operation, however a key component of that model, salt domes, is not a part of Kentucky's subsurface geology and thus is not an option for implementation in Kentucky. Of the seven CAES models reviewed here (Figs. 1 and 9), likely the conversion of abandoned limestone mines to compressed air storage would be easiest, although costs for a limestone mine conversion to compressed air storage would widely vary depending on mine conditions. Four inactive and six abandoned limestone mines were identified in this study (Fig. 4) as possible candidates for hosting compressed air storage for a CAES electricity power generation plant. These mines would require geotechnical assessments of their integrity and their available compressed-air storage volumes to proceed with a CAES project. The other two models requiring caverns for storing compressed air, acid solution-mined caverns (Fig. 3) and the A-CAES mined cavern (Fig.6), require lengthy construction periods before installation of the CAES power generation plant. Both solution-caverns and abandoned limestone mines CAES air storage models, if the storage cavern is sufficiently deep below the surface, may benefit from hydrostatic stored air pressure compensation as proposed for the Hydrostor Inc. A-CAES electricity generation plants (Fig.6). Two CAES potential compressed-air storage reservoirs (Fig.5), abandoned oil and gas fields and aquifer storage, require sufficiently porous and permeable subsurface geologic reservoirs below fracture depth for compressed air storage. Thus, to store compressed air at 1,100 psi as it is at the PowerSouth McIntosh power plant, a porous and permeable reservoir with overlying confining strata would have to be deeper than about 1,835 ft (storage reservoir minimum depth = reservoir pressure/fracture gradient [0.60 psi/ft in Kentucky, above]). Low-pressure air storage, comparable to 870 psi at the proposed Hydrostor Inc. Pecho Energy Storage Center, could be as shallow as about 1,450 ft with the same overlying confining strata requirement.

Plots of the permeability values measured in cores during this study, including comparison to the lab values measured in the 1960s, are found in Appendix 2a. Although the plotted values are comparable, our values are almost entirely an order of magnitude or more lower. The cores are 50 years old, dry, and have been moved many times so damage to the original permeability is a possible explanation for the differences. The survey made as part of this study did not find oil and gas field reservoirs in Kentucky with the minimum properties outlined by Pacific Northwest Laboratory (2013), even though these fields had produced economic volumes of hydrocarbons. The limiting factor for air storage in lower permeability abandoned oil and gas or aquifer reservoirs will be the compressed air charge/discharge flow rate: a low compressed air flow rate would limit the electricity production from the CAES power plant. A porosity-permeability cross plot of the Tar Springs Sandstone, the principal oil and gas reservoir in western Kentucky, is shown in Appendix 2b. Using Pacific Northwest Laboratory's (2013) cutoff for what would be an acceptable compressed air storage reservoir, not much of the Tar Springs would be useful. The most promising CAES model reviewed in this study is cased wellbore CAES (Sarmast and others, 2021; CleanTech Geomechanics, 2021; Figs. 8 and 9; U.S. Patent 2021/0024290A1). The advantages of CW-CAES are that project siting is independent of subsurface geology and a CW-CAES project is easily scalable from microgrid to major-utility scale. Compressed air storage volume for a CW-CAES, hence the electricity generating capacity of the CW-CAES project, is controlled by the number of compressed air storage wells installed for the project (Figure 9). Where Sarmast and others (2021) and CleanTech Geomechanics (2021) proposed high-pressure, high-temperature compressed air in 10-in cased wellbores, however, here I propose larger cased wellbores, lower compressed air storage pressure, and lower stored compressed air temperature. In this model compressed air is heated at the surface during discharge from the storage wells using surplus electricity generated by the co-installed PV solar generation facility and stored in associated capacitors or batteries. Wellbore depth and casing diameter, 3000 ft effective depth and 20-in OD/18.73-in ID (Fig. 9), are uniform across the project site and estimated energy storage for each wellbore is about 3.4 MW-hours. With wellbores spaced 50 ft apart in 0.15-acres per hexagonal patterns, to allow servicing access, a utility-scale 200 MW-hour project would require only 4.4 acres to accommodate 64 compressed air storage wellbores (Fig. 9).

3.1 Economics

Many papers have been published during the last two years discussing the economics of CAES electric power generation around the world. For example, estimated capital costs have been $1050- $2544/kwh for a solution salt cavern project (Mongrid and others, 2019; Mongrid and others, 2020a; Mongrid and others, 2020b; Balducci and others, 2021) or high-temperature CAES (Cárdenas and others, 2017). The U.S. Department of Energy (2020) estimated that the CAES U.S. domestic resource potential at 121 GW considering only salt dome and salt bed solution caverns and aquifer storage. They also noted that many sites tested in the U.S. were inadequate because of poor rock porosity in potential compressed air storage reservoirs and cited proposed projects in Ohio, Iowa, and the PG&E site in California, discussed above, as examples (U.S. Department of Energy, 2020). U.S. Department of Energy (2020), however, estimates that CAES could be competitive with lithium-ion battery storage for about 60 Gigawatt-hours of electrical capacity by 2030, although further research would be required (Sheppard, 2021).

3.2 Pore Space Ownership

The issue of pore space ownership is an important, but addressable potential barrier to any project related to land use, especially in Kentucky where surface ownership and mineral rights are often severed. Pore space ownership is addressed under both state and federal law, generally from the standpoint of natural gas storage in depleted gas fields (Burt, 2016). The Federal Energy Regulatory Commission regulates natural gas storage in the United States. As of August 2021, Kentucky had 187.0 billion cubic ft of natural gas stored in gas storage fields (U.S. Energy Information Agency, 2021b). Kentucky specifically addressed pore space ownership in legislation addressing subsurface storage of carbon dioxide (Kentucky Revised Statutes Chapter 353; KRS 353.800B353.812, effective 08 June 2011), where A Pore space owner means the surface owner unless the pore space has been severed from the surface estate, in which case the pore space owner shall include all persons reasonably known to own an interest in the pore space; Definitions for KRS 353.800 to 353.812.

Pore space is only applicable to CAES development when compressed air is being stored in subsurface porous and permeable geologic reservoirs or aquifers (Fig. 5) where the CAES developer is not the surface landowner, or the mineral rights have been severed from the surface. This type of storage reservoir would also require an EPA injection permit, which would typically be categorized as a Class V but could vary based on the impact of compressed air on groundwater at a specific site. All other CAES models considered in this project should not have an impact on porosity or groundwater, although they may require other State and Federal permits.

3.3 Social Equity, Environmental Justice and CAES

Because CAES is both site-flexible and easily scalable, it provides a starting point for the conversation surrounding energy equity in the U.S. (Pacific Northwest National Laboratory, 2021, PNNL-31451). Tarekegne and others (2021) developed four social justice tenants where energy storage can play a major role: distributive justice, recognition and procedural justice, and restorative justice. Distributive justice is an equity principal where people should have sufficient access to reliable and quality energy systems and resilience to natural disasters (Tarekegne and others, 2021). CAES, as a modular solution to energy availability (Figure 8) could be constructed to offset inequities in the siting and distribution of fossil fuel energy production while supporting grid reliability. Recognition equity and justice is the concept that individuals and communities must be fairly represented in the decision making process surrounding energy distribution (Tarekegne and others, 2021). Here, CAES energy storage systems could be strategically sited to support communities underserved by the present energy system through utilities subsidizing co-ownership of the storage assets. Environmental justice is meaningful involvement and fair treatment of people of all social-economic backgrounds by and ensuring that no group should be disproportionately burdened by the negative environmental consequences stemming from industrial, governmental, and commercial operations and policies (Kentucky Energy and Environment Cabinet, 2022). It is a fundamental right of environmental self determination for the people to participate as equal partners in every level of energy decision from initial assessment of needs to implementation of plans (Ramirez-Andreotta, 2019). This fails in electrical power generation where, for example, fossil fuel electric power plants are disproportionately located in or near disadvantaged communities (2021, PNNL-31451).

As a replacement for conventional fossil fuel electrical power generation in Appalachia, CAES with co-installed PV solar power generation could generate regional employment. Work to integrate social equity or economic concerns with energy goals would require collaboration with other regional groups and researchers, including the UK Center for Appalachian Research in Environmental Sciences (UK-CARES) to evaluate community needs. In the end, the successful installation of CAES with co-installed PV solar electricity generation could be a path to equitable power generation for all Americans (see the discussion in Michener and others, 2021).

4. Conclusions

CAES with co-installed PV solar electricity generations provides a variety of options for non-fossil fueled power in Kentucky. Of the seven CAES models discussed in this report, those most likely to be easily implemented are the conversion of inactive and abandoned limestone mines to compressed air storage at 10 sites in Kentucky, along with either cased-wellbore, CW-CAES, model. The independence of the CAES, particularly the co-installed CAES and PV solar model, from fossil fuels positions it as an environmentally safe, feasible alternative for equitable electrical generation in Kentucky.

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6. Appendices

Appendix 1. Inventory of Kentucky limestone mines including active, inactive, and abandoned mines.

Appendix 1a. Active limestone mines

Appendix 1b. Inactive limestone mines

Appendix 1c. Abandoned limestone mines

Appendix 2. Tabulation of permeability measurements performed on western Kentucky cores during this study and porosity/permeability of Tar Springs Sandstone legacy data.

Appendix 2a. Permeameter Plots

Appendix 2b. Tar Springs k-phi Crossplot

Disclaimer

The Kentucky Geological Survey (KGS) does not warrant the accuracy or completeness of any data, information, or interpretations used or presented herein, including figures presented with the text and any interpretations that may be, or have been, made from them. Nor does KGS warrant the use of any data, information, or interpretations used or presented herein for any purpose including but not limited to financial investments of any kind.