



## Review Article

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# Abandoned Mine Voids for Pumped Storage Hydro

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## Abstract

Pumped Storage Hydro (PSH) is geographically limited but can expand greatly if abandoned subsurface coal mines are leveraged for the lower reservoir. Such lands are already permitted, generally less desirable, and found in regions eager for job creation. Vertical stacking of the upper and lower reservoirs is an efficient use of the land. Water can be raised by electric pumps as part of energy arbitrage; however, water can also be raised with Hydraulic Wind Turbines. HWTs are far less costly than traditional electric turbines, and start-up at lower wind speeds - thereby extending their geographic range. The HWT masts can serve double duty as tent poles to support translucent architectural fabric over the surface lake. This prevents evaporation and ingress of wildlife, and provides an interior space useful for non-electric revenue, such as aquaculture and greenhouses. Water cycled through the system can, in some cases, supplement local sources. Seepage through water tables replenishes clean water. Subsurface water is cool and can be circulated through server farms in data centers which represents a potential revenue source that can be started up well in advance of the primary energy storage operation. Combined, these factors bring an innovative solution to site selection, design, and engineering for PSH which promises accelerated commissioning and permitting, and low-cost operation. The bottom line for communities in Coal Country is more jobs and cheaper power.

**Keywords :** Abandoned Mine Lands; Pumped storage hydro; Wind turbines; Coal pillars; Erosion; French drains; Natural gas; Power Usage Effectiveness; Nutraceuticals

## Introduction

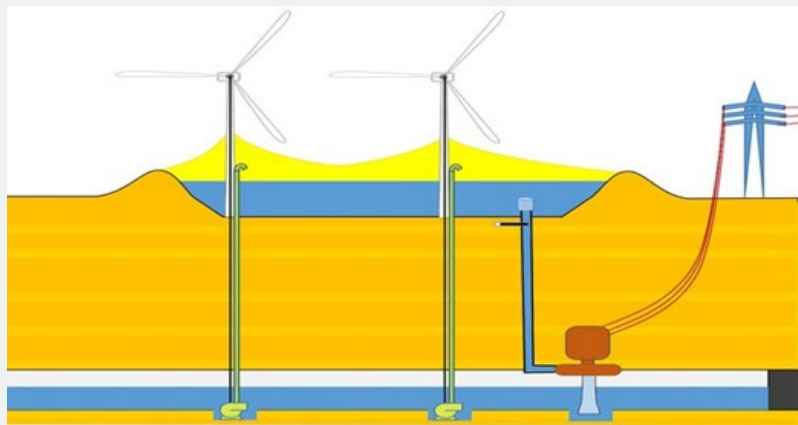
This novel concept includes individual elements studied in detail, however, not coupled to enable the suite of benefits this system provides: low cost, low risk, and short duration. Abandoned Mine Lands (AML) have been studied extensively in many states, including Indiana [1-5]. The use of mine voids for pumped storage hydro (PSH) has been studied in Austria and in the US, but none have included the innovative use of hydraulic wind turbines (HWT). Hydraulic technology is quite mature with products in the mining and oil and gas industries. Components in an HWT last longer and are significantly less massive than conventional electric wind turbines. HWT installations are lower in specific cost, and can start-up with lower wind speeds. Lightweight HWT pumps can be mounted on tall masts to take maximum advantage of the moderate wind resources generally found around Midwest mine lands. Construction work is straightforward, including the formation of a surface lake of 250 acres to a depth of 33 feet. The upper reservoir is lined with bentonite clay, and the shore lines with rip-rap [6-12]. The lake is then filled from local subsurface water. Many communities already use subsurface

reservoirs from coal mining for drinking their water - this being fairly common in Kentucky. Although some abandoned mines have left environmental problems without funding for remediation, our concept includes repurposing of these lands using the skills of coal miners who have lost work due to slackening global demand. Should seepage be excessive the mine walls can be coated with spray-applied shotcrete. Shotcrete protects coal pillars, from a rooms-and-pillars extraction method, eliminating erosion from water cycling. French drains (lowered culverts) in the underlying rock will be used at the outlet of the turbine generators to further minimize coal erosion. Cycling of water daily as part of PSH provides ample opportunity for filtration and treatment. Fresh water from precipitation, and clean water from underground, contribute to a potable product which can be sold into local water utilities, or released into nearby streams. State and local governments are often motivated to ease and accelerate the permitting process for the benefits provided in jobs, revenue, and environmental clean-up, such as the Mineville project near Moriah, NY, USA. All mine operations required by this new

concept are well-established. Pipes are all vertical, the penstock is buried, and there is no boring – factors which greatly reduce cost and development time. Many challenges faced by conventional PSH schemes are simply absent with PSH on AML with HWT. Equipment is cheaper. Dirt movement is minimized. Specialized labor is reduced. Many forms of environmental impact are obviated. Construction can be completed in three years.

Firming nuclear power was a strong motivation for the early US lead in PSH, but no new PSH installations have been built in 20 years, and only three are under consideration (Eagle Crest, Golden Butte, and Swan Lake, all in the Western US). A new need is rising because the utility-scale levelized cost of energy (LCOE) for wind and solar are now lower than for new installations of coal or natural gas. With low cost PSH to firm intermittent renewables, electricity rates can be reduced, and overall environmental harm from power generation can be greatly reduced. The powerful forces and strong public opinion in this direction will soon overcome organizational inertia, conservative risk aversion, and regulatory near-term focus of many Public Utility Commissions and utility Integrated Resource Plans. Competition comes from batteries. There is a narrowing window of opportunity to advance PSH before battery costs drop low enough to preclude PSH forever. Our team has studied auxiliary revenue

sources, beyond energy arbitrage and grid level services (e.g. load leveling, voltage regulation, power quality). Of particular interest is the use of subsurface cooling water for data centers, which can be started in advance of the start-up of the PSH function. Data centers are huge energy consumers (10-50 MW) [13-16]. Power Usage Effectiveness (PUE) is how data center operators measure how clean their operations run. Cool subsurface water can save up to 20% of annual costs, paying back data center capital expenditures (CAPEX) every year! Some US States offer tax incentives to encourage siting of data centers within their borders. When using the HWT energy to power the computer chips, the “green” factor becomes very attractive. Other auxiliary revenue generators include flooding ponds for raising sustainable protein from fish or growing specialty algae for nutraceuticals or fuel. Hydroponics suspended above the lake can provide fresh produce locally to regions far from the sunny climes where salad ingredients and fresh vegetables are typically grown and shipped from. Diet improvement to communities where obesity is rampant could become significant. It is even possible to use architectural transparent membranes, hung between the HWT masts, to enclose the interior [17-20]. In addition to providing security to the site, it can even be used for year-round recreation, vertical greenhouses, botanical gardens, and other uses to be discovered by local innovators (Figure 1).



**Figure 1:** Conceptual design for integration of Hydraulic Wind Turbines with Pumped Storage Hydro on Abandoned Mine Lands for grid-scale energy storage.

### Charge and Discharge

In this design, there are several water pumps that are driven by hydraulic motors. These hydraulic motors are driven by hydraulic pumps at the wind turbines. The shafts of these hydraulic motors are independent of each other and of the hydro-turbine generator to generate electricity.

#### Means of charge

- a) The wind turbine-driven water pumps. The principle is that the wind turbine rotates a hydraulic pump on top of

the tower. The pump circulates a pressurized medium in the closed-loop system to drive a hydraulic motor in the bottom of the reservoir. The hydraulic motor is coupled to a water pump that is used to pump the water to the upper reservoir.

- b) Several wind turbines can drive a common hydraulic motor (coupled to a water pump).

- c) The hydro turbine-generator set can be used as a water pump to charge the upper reservoir. In this case, the electricity is taken from the grid to charge the upper reservoir.

**Means of discharge**

- a) The hydro turbine-generator set is used to discharge the water from the upper reservoir and generate electricity.

**The operation of the storage can be categorized as follows:**

- a) The upper reservoir is at the minimum level. The production of electricity is stopped. Wind-driven hydraulic pumps are set to the maximum power to fill the upper reservoir. Wind Turbine MPPT and the water pump speeds are controlled independently [21]. Since the shaft of the wind

turbines and the shaft of their water pumps are mechanically isolated, these two control objectives can be achieved.

- b) The upper reservoir is between the minimum (~30%) and maximum (~80%) capacity. The water level (height) is high enough to enable harvesting of significant energy. In this case, the hydro turbine-generator is used to generate electricity. The wind turbines continue to pump the water to the upper reservoir while the reservoir is being discharged through the turbine. In this case, the charge and discharge of the upper reservoir occur simultaneously (Figure 2).

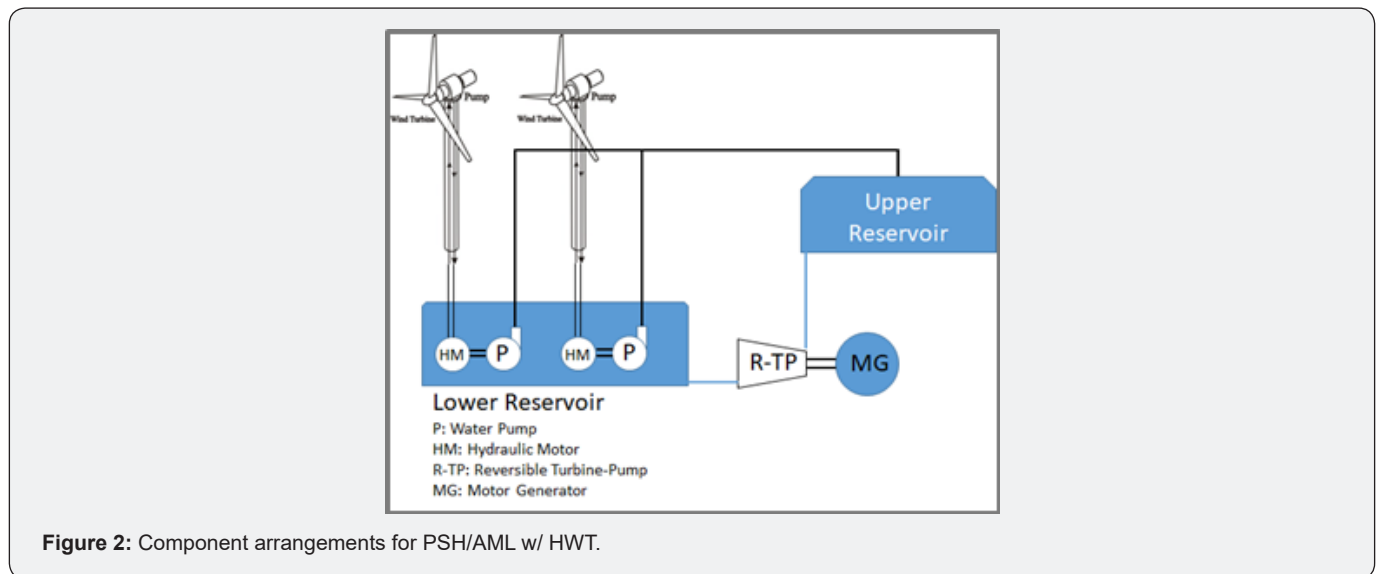


Figure 2: Component arrangements for PSH/AML w/ HWT.

**Technical Challenges**

Water quality is the #1 most-cited concern, as discovered by our team from the School of Public and Environmental Affairs. This concern was explored by team members from the Indiana Geological and Water Survey, who determined that this issue is quite manageable, and that many communities use coal mine voids for drinking water - it meets all EPA requirements. Mine integrity is an issue to consider [22-24]. Our answer is to leverage shotcrete to shore up the remaining coal pillars, and to use French drains on the floor for higher-velocity water jets downstream of the turbine-generator. Additional measures may be required, depending on local geology. Upper reservoir erosion is a concern in the non-tented version, as the topsoil is deep in the Midwest and the PSH system is expected to be used daily. In addition to the Bentonite clay lining, a 3mm or thicker polymer liner may also be required.

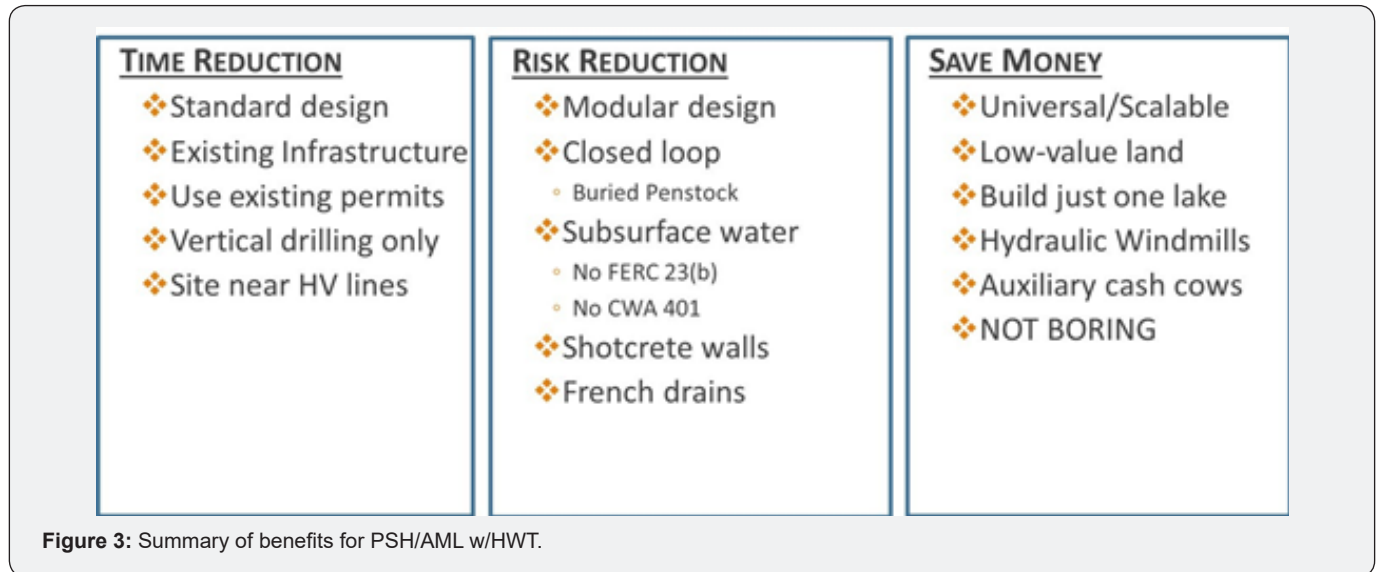
**Economic Feasibility**

There are some 400,000 abandoned mines in the US, 190,000 which are below ground, and at least 5000 of various size in the Midwest. While each mine has unique characteristics, our approach is to modularize the PSH/AML w/HWT and carry three design sizes. The nominal module for costing is a mine void

having 400 feet of head, and a pumped-storage system delivering 200 MW for 7 hours. A reversible Francis turbine at this rating costs approximately \$70M installed and commissioned. The subsurface powerhouse is \$3M. The upper reservoir is slightly larger than the underground void and is 250 acres times 33 feet, or 8250 acre-feet (AF) of volume. Using Illinois excavation cost estimates for reservoirs and doubling their formula to include a Bentonite clay liner plus ample shoreline riprap (perhaps from French drain excavation) is \$10M. Fencing around such a lake is \$0.5M, and filtration (20 units) costs \$13M. Steel piping of 5 ft. diameter is \$14.8M and up-pumps of 2000 AF/min are \$50M for two such units. Shotcrete to line the walls of a coal mine is the largest single expense at \$100M, with total labor costs over 3 years of \$2.3M. Assuming that electrical transmission lines are nearby (likely in southern Indiana and Illinois coal country), the interconnect infrastructure is estimated at \$50M. The total cost for this 200 MW, 1400 MW-hour PSH system is just under \$300M, or \$1,494/kW. A study of non-electric, auxiliary revenues based on server farms, hydroponics, and aquaculture show total addressable market (TAM) sizes for a 5-state region surrounding Indiana of \$20.1B, \$6.1B, and \$73M, respectively. Co-location with paper mills or steel rolling bring further TAM of \$3.4B and \$4.7B. These auxiliary revenues improve the eco-

conomic efficiency and reduce financial risk for funders as these operations can start early and begin to provide cash flow. This

arrangement is likely to attract a lower discount rate than more traditional projects (Figure 3).



### Market Feasibility

Wind and solar operations at the utility-scale are currently much less expensive than new installations of coal or gas thermal plants. A 2019 report by McKinsey forecasts parity between wind and existing coal plants before 2030! Meanwhile, energy prices are forecasted to continue rising in Indiana, where the ranking for electricity rates has slid from the top 10 to number 33 in two decades. A widely-held concern with non-dispatchable wind and solar is that intermittent power production adversely affects certain manufacturing operations. Because Indiana is the number 1 state for manufacturing intensity (per capita), reliability of power is paramount to decision-makers. Introducing grid-scale energy storage using PSH/AML/HWT provides stability for these low-cost resources. In this way, our concept overcomes the primary objection to renewables, and at the same time lowers the cost of electricity. The boost in attracting manufacturing jobs to Indiana is considerable, as our power becomes cheaper and also greener! The day-ahead market run by Independent Systems Operators (ISOs) do not provide long-term commitments to energy arbitrage, lowering its appeal to financiers. Funder may also weigh capital costs against competing energy storage systems such as vanadium redox flow batteries. Yet the specific costs for our system are significantly lower than batteries. Installation time is longer than for batteries, but much faster than traditional PSH. Therefore, we believe that with an early start, through winning this competition, we can introduce technology which has long-term potential to participate in grid-scale storage on an hourly, dispatchable basis, as well as on a seasonal basis if needed to address challenges with generation fleets in the future. Arbitrage of energy with the low specific capital cost for PSH/AML are economically viable. Ramp-up for PSH can occur in under six minutes, matching all but the most advanced

natgas peaking plants. Multi-hour operation to flatten the “duck” curve is an excellent pairing to solar power, where PSH/AML can provide user needs in the evening hours. Non-electric revenues arising from our innovative concept have, within a 5-state region, a TAM market of \$137 billion in annual revenues. These can be added incrementally, making the entire system flexible and adaptable as market needs shift [25,26].

Environmental concerns have been addressed above regarding water and gob piles. Many AML sites are disused, being unsuitable for agriculture. Such lands are of low value, and thus can be obtained for below- market rates. Land use changes away from productive activities are minimal. Local economic development agencies are hungry for solutions to boost revenue from abandoned mine lands. Very few alternatives are forthcoming. The repurposing of subsurface voids meticulously excavated over many years to extract fossil fuels can now pay a dividend in boosting renewable energy through firming of intermittent solar and wind. The work required in construction of the PSH/AML project will transform these marginal lands to full productivity. The operation of water cycling for energy storage provides motivation and opportunity to clean up the water from leachates accumulated over decades. The overall environmental impact assessment should be net positive, and that, to a significant degree [27-29].

### Conclusion

Non-performing and low-value land can be converted to grid-scale energy storage which has several auxiliary revenue streams beyond the day-ahead energy arbitrage market. Some of these additional value streams can begin generating cash in advance of the primary economic function of the PSH system. Utility-scale installations of wind and solar power are now su-

perior in levelized cost of energy (LCOE) compared to natural gas and coal-fired thermal power plants. Their intermittent nature can be addressed by grid-scale storage, which can be met economically with the conversion of abandoned mine lands and the addition of hydraulic wind turbines. This method of energy storage provides more benefits than any other method.

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