Gravity Batteries for Integrating Renewable Energy into Power Grids

SAJU, Febin K and AKMAL, Muhammad <http://orcid.org/0000-0002-3498-4146>

This document is the Accepted Version [AM]

Citation:

SAJU, Febin K and AKMAL, Muhammad (2025). Gravity Batteries for Integrating Renewable Energy into Power Grids. In: 2025 IEEE International Conference on Environment and Electrical Engineering and 2025 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe). IEEE. [Book Section]

Gravity Batteries for Integrating Renewable Energy into Power Grids

Febin K. Saju

School of Engineering and Built Environments,
Sheffield Hallam University,
Sheffield, United Kingdom
febinksajupullad@gmail.com

Muhammad Akmal [*]

School of Engineering and Built Environments,
Sheffield Hallam University,
Sheffield, United Kingdom
m.akmal@shu.ac.uk

Abstract—**The growing adoption of renewable energy sources, such as wind and solar power, has introduced new challenges in maintaining a stable and reliable electricity supply. This paper explores the potential of gravity battery systems as an innovative solution to address the intermittent nature of renewable energy generation and enhance demand-side management. With the increasing emphasis on reducing greenhouse gas emissions and transitioning to a sustainable energy future, finding efficient methods for energy storage and utilization is of paramount importance. The core focus of the research is to determine the optimal capacity of gravity batteries required to effectively smooth out renewable energy fluctuations and support grid stability. This paper commences with an extensive analysis of the current electricity consumption patterns in Britain, using historical data and trends to understand the variations in energy demand, and indicates that repurposing abandoned mines for gravity-based energy storage offers a viable solution. This information serves as a benchmark for evaluating the feasibility and efficiency of gravity battery integration. MATLAB simulation evaluates gravity battery integration feasibility and efficiency, determining optimal capacity to smooth renewable energy fluctuations and support grid stability.**

Keywords—**Gravity battery, energy storage, demand side management, wind variability management**

I. INTRODUCTION

Gravity Energy Storage (GES) presents an innovative approach to sustainable energy solutions, utilizing gravitational potential energy to store and release energy efficiently. By lifting and lowering a mass, gravity batteries convert gravitational energy into electricity, offering scalable and adaptable storage solutions. With applications in balancing electricity supply and demand and serving as reliable backup power during grid failures, GES complements intermittent renewable sources like solar and wind. Operating on fundamental physics principles, gravity batteries boast efficiency, longevity, low maintenance, and scalability, synergizing well with other renewables to create effective clean energy systems. Positioned to revolutionize energy storage, GES offers promising prospects in renewable energy integration and grid stability by harnessing nature's fundamental force [1, 2].

In recent years, renewable energy has become crucial in meeting the electricity demands of residential and commercial sectors. The UK has shown strong commitment to transitioning to an electricity infrastructure primarily fuelled by renewable and carbon-neutral resources. In 2020, renewable energy sources contributed to 43% of the nation's power generation, marking a historic shift. This achievement is due to the diverse energy mix, including wind, solar, bioenergy, and hydroelectric power, demonstrating the UK's dedication to reducing its carbon footprint. On May 15, 2023, the UK celebrated producing its trillionth kilowatt-hour (kWh) of electricity from renewable sources, showcasing its commitment to cleaner energy and its potential to inspire other nations. [3].

II. LITERATURE REVIEW

A. Energy storage technologies

Battery storage systems are crucial for global energy storage, with various types tailored to specific grid applications. Compressed Air Energy Storage (CAES) compresses and releases air to manage large electricity loads during high demand [4]. While advanced, CAES and Pumped Hydro Storage (PHS) face efficiency challenges and long construction times due to geological requirements [5]. Flywheel Energy Storage Systems (FESS) offer compactness and longevity but entail high setup costs and limited energy release [6]. Pumped hydro storage, a reliable grid-scale method, pumps water uphill during excess electricity and downhill during high demand, improving grid stability and integrating renewables. Variable-speed units in pumped hydro storage offer advantages over constant-speed ones, but traditional systems need large, inclined land areas [7]. The innovative "Gravity Battery" system captures pumped hydro storage benefits while overcoming spatial constraints.

B. Gravity Energy Storage

Gravity Energy Storage (GES), or Gravity Batteries, evolved to address geological constraints and environmental concerns of traditional Pumped Hydro Energy Storage (PHES). Innovations like single-reservoir systems, Compressed Air Energy Storage (CAES), solid mass storage, and vertical shaft storage aim to enhance versatility and reduce location dependence, overcoming challenges of PHES. Ongoing research focuses on materials and designs to improve GES efficiency, promoting a flexible and sustainable approach to large-scale grid energy storage. [8].

III. METHODOLOGY

The UK has numerous abandoned shaft mines from its coal and mineral extraction history, posing challenges like land subsidence, water pollution, and gas emissions. Government and organizations are working to monitor and manage these mines, exploring repurposing options. With

979-8-3315-9515-9/25/$31.00

metal mining dating back over 2,500 years and peaking in the 18th and 19th centuries, thousands of metal mines are now abandoned across the country [9]. Utilizing abandoned mineshafts for solid gravity battery storage (Shaft Solid Gravity Battery) presents a sustainable concept, offering a practical means of repurposing these disused mining structures for the storage of energy. Figure 1 illustrates the Shaft solid gravity battery system with suspended weight. In this diagram, H represents the height of the weight, d signifies the diameter, L denotes the depth of the shaft, L' is equal to L-H. representing the depth available for energy storage, and Rs stands for the radius of the traction sheave [10].

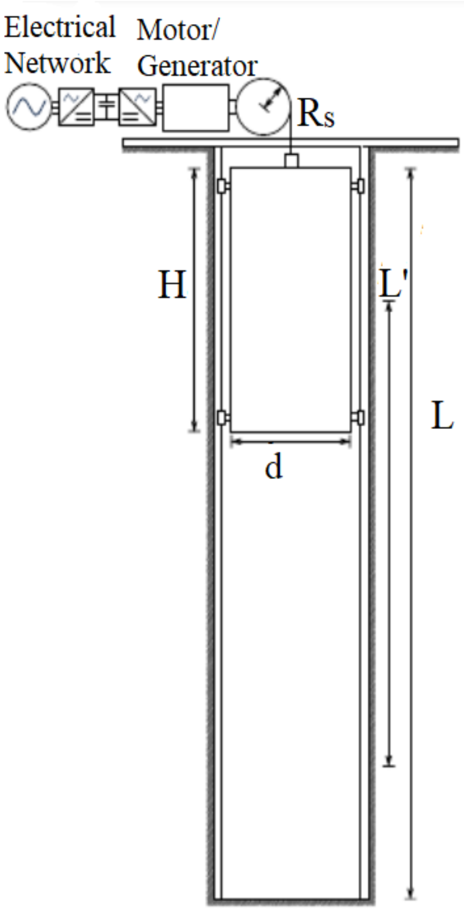

Fig. 1. The Shaft solid gravity battery system with a suspended weight [10].

A. *System Specifications*

This part examines how to make the suspended weight as big as possible to store the most energy in the system. It also looks at the power capacity needed for the motor and power electronics to reach a specific ramp rate. It is presumed that the system employs a cylindrical weight. The system's capacity to store energy is defined by the following,

$$E = \eta m g L'$$

The usable depth of the shaft for storing energy is denoted as L', where η represents the round-trip efficiency, m is the mass of the Hanging weight, and g is the acceleration due to gravity. The height of the cylindrical weight is represented by H, and its diameter is denoted by d.

The volume is then given by.

$$\mathbf{V} = \frac{\pi d^2 H}{4}, \tag{1}$$

$$\mathbf{H} = \frac{4V}{\pi d^2} \tag{2}$$

The mass of the weight, made from a material with density σ, is given by m = σV. For a shaft with a depth of L, the usable depth of the shaft for lifting the weight is expressed as L' [11].

$$\mathbf{L' = L - H = L} - \frac{4m}{\pi d^2 \sigma} \tag{3}$$

Hence, the complete capacity for storing energy is, determined by the following [9],

$$\mathbf{E = \eta\,(mgL} - \frac{4mg}{\pi d^2 \sigma}\,) \tag{4}$$

Elevating the height of the cylindrical weight results in an increase in mass while simultaneously decreasing the usable shaft depth, introducing a trade-off in energy capacity. This trade-off is reflected in the derivative of the energy capacity concerning mass.

$$\frac{dE}{dm} = \eta \left(\mathbf{gL} - \frac{8mg}{\pi d^2 \sigma}\right) \tag{5}$$

Moreover, there could be a practical limit, for the maximum mass the suspended weight can handle considering the ropes and support structure. Considering this limitation, the mass that optimizes the energy storage capacity is determined by the following. This is synonymous with determining the dimensions of the suspended weight cylinder to achieve a specific height [10]. That is,

$$\mathbf{L'} = \frac{4m'}{\pi d^2 \sigma} \tag{6}$$

Storing maximum energy in small diameter mine shafts is limited because increasing the mass of the cylinder reduces usable storage space, requiring a larger height and diminishing shaft depth. Mines over 400m can only store 1MWh of energy with a minimum weight of 3500 kg. The most powerful crane in the world has the capability to hoist weights of up to 20,000 tonnes [12], [13]. To find the properties of the suspending rope, steel wire ropes are preferred for elevators due to their redundancy, detectability, reduced abrasion with parallel strand construction, extended fatigue bending life, and minimal wear on sheaves. [14]. The steel rope used for heavy lifting application having density 4,706 kg/m^3 and Cross-sectional area(A) is 32.84 mm^2 [2] can be considered for the design of Gravity battery. The minimum length of the rope (L) must be 400m.

Volume of the rope (V) = A.L

Mass= V. density of the rope

Mass= $4706\text{kg/m}^3\times(32.84\times10-6\text{m}2\times4\text{m})$ = 0.062kg

This corresponds to a wire with a diameter of approximately 6.5 millimeters, which is negligible compared to the 3500-ton load weight.

B. Power Electronics Control in Gravity Battery System

In integrating a gravity battery storage system with the electrical grid, adherence to established grid operator and regulatory agency standards is paramount. This includes rigorous assessment of system components, particularly power electronics, to ensure compliance with technical requirements such as frequency and voltage levels. During the lifting phase, the induction motor functions as a motor, converting electrical energy from the grid into mechanical energy to elevate the weight, managed precisely by the power electronics control system. Subsequently, in the releasing phase, the control system adjusts generator speed to match grid frequency, ensuring smooth integration and optimal operation in response to load and grid conditions. Voltage and frequency control mechanisms are employed to regulate electrical output, maintaining grid compatibility and stability. Additionally, fault detection and diagnostics play a crucial role in identifying and addressing abnormalities or malfunctions within gravity battery components, enhancing system reliability and performance.

C. Abandoned Mines in UK and its Storage capacity.

In the UK, 2.4 GW or 2.6 GWh of active energy storage is distributed across 161 locations, with 20.2 GW in planning stages for approval. Integrating a mineshaft gravity battery into the grid could improve grid stability by utilizing gravitational force for energy storage and release, contributing to reliability. There are 11 coal mines over 400 meters deep [15]. However, most coal mines in the UK are closed or inactive, with the last deep coal mine, Kellingley Colliery, shutting down in December 2015. The only currently operational coal mine with a depth exceeding 400 meters is the Boulby Mine, which extracts potash and has a depth of 1,400 meters and all these mines have minimum width or diameter more than 8 meters [15], [16]. So, the height of the load with cylindrical shape and mass 3500 tons can be calculated as

$$\boldsymbol{h}=\frac{\boldsymbol{m}}{\boldsymbol{\sigma\pi r^2}} \qquad (7)$$

Substituting the values,

$$\boldsymbol{h}=\frac{\mathbf{350000}}{\mathbf{4706\times\pi\times4^2}} = 14.88\text{m} \qquad (8)$$

The design of the gravity battery minimizes space requirements, making it feasible for installation within mines. This efficient use of space is advantageous given the depth of mines and their energy production potential, affirming the practicality and viability of constructing a gravity storage battery within mining facilities.

D. Harnessing Mineshaft Gravity Battery with grid for Sustainable Energy Demand Management in Britain

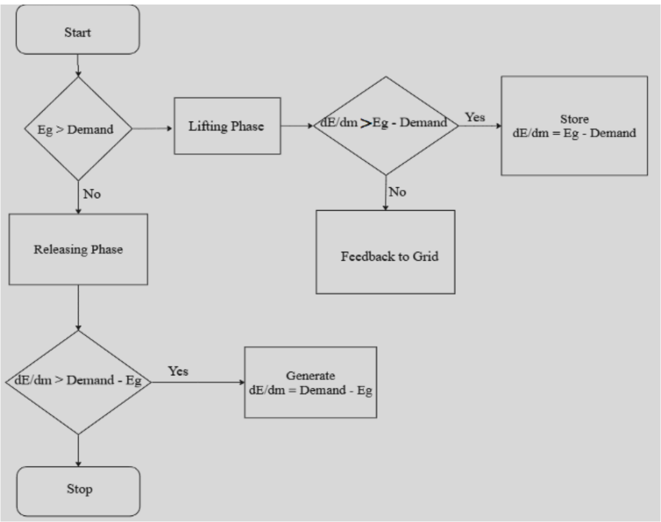

Fig. 2. Flowchart of Shaft solid battery integrating with grid

where “Eg” represents Energy in the grid and dE/dm is the storage capacity of the gravity battery.

The flowchart outlines actions based on energy supply and demand: When grid energy exceeds demand, the battery assesses its capacity to store the excess and does so until full or provides feedback to the grid if capacity is insufficient. Conversely, if grid energy is insufficient, the gravity battery generates electricity to meet the demand, with continuous monitoring to halt generation if capacity drops below demand, ensuring balanced energy supply.

E. Harnessing Mineshaft Gravity Battery with Wind energy generation for Sustainable Energy Demand Management

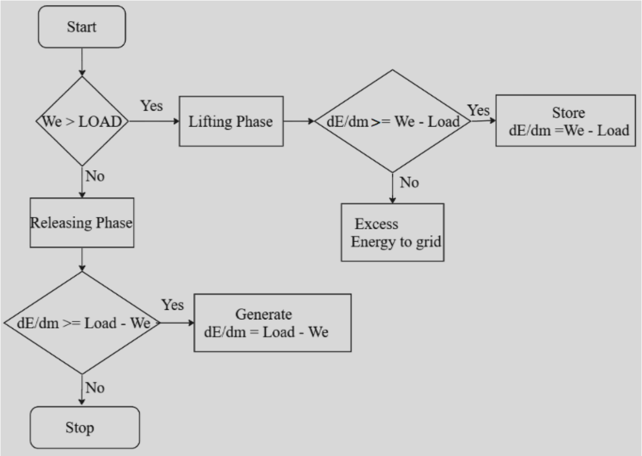

Fig. 3. Flowchart of Shaft solid battery integrating with Wind energy

where “We” represents the Wind Energy generation and dE/dm is the storage capacity of the gravity battery.

Wind power significantly contributed to the UK's energy mix, accounting for 26.8% of total electricity generation. In November 2022, wind produced over 20GW of electricity for the first time, exceeding 70% of that day's generation. This record was repeatedly broken, with the highest generation of 20.918GW occurring on 30 December [9]. So, if this wind energy can store in gravity battery it has several advantages, Gravity batteries optimize renewable energy use, storing excess wind energy to reduce curtailment and fossil fuel reliance, ensuring a cleaner, sustainable energy system. [17]. Abandoned mines can store energy as gravity storage, charging during abundant wind generation and discharging when wind is less available. This supports Demand-Side Management (DSM) to handle wind power variability effectively.

The flowchart outlines the operational logic of a gravity battery system with wind energy. When wind power exceeds demand, the battery stores surplus energy. If capacity allows, it stores efficiently; otherwise, excess energy returns to the grid, ensuring optimal utilization of storage capacity and managing the energy balance effectively.

In the releasing phase, the gravity battery converts stored potential energy into electrical power to supplement the existing supply when wind energy falls short of demand. If stored energy exceeds the difference between demand and wind generation, the battery engages in electricity generation until reaching capacity or fulfilling demand. Otherwise, generation halts to avoid exceeding storage capacity. This approach ensures a balanced response to varying energy conditions, stabilizing electricity supply during low wind production.

IV. RESULTS

A. *Energy Storage Capacity of Gravity Battery*

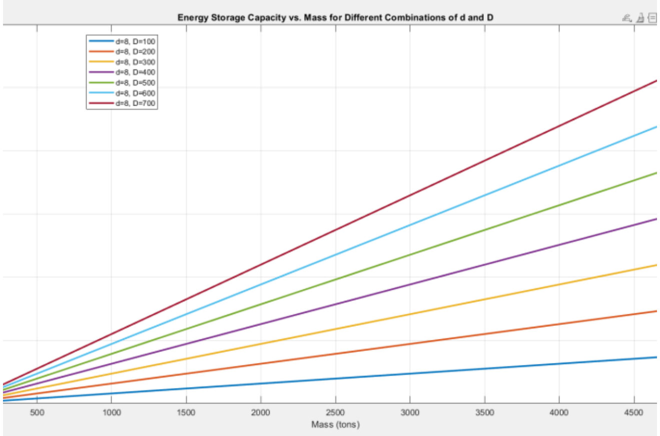

Fig. 4. Energy Storage Capacity of Gravity Battery subjecting to different mass and Depth.

Where ‘d’ is the diameter of the cylindrical weight and ’D’ is the Depth of gravity storage. The graph in Figure 4 highlights that achieving a 1 MWh capacity for the gravity battery requires a minimum depth of 400 meters, associated with a weight of around 3200 tonnes. It emphasizes that this capacity cannot be reached with a weight of 3500 tons at depths below 300 meters. As depth exceeds 500 meters, there's a notable reduction in required weight for the same capacity, suggesting a proportional relationship between depth and mass needed for efficient energy storage.

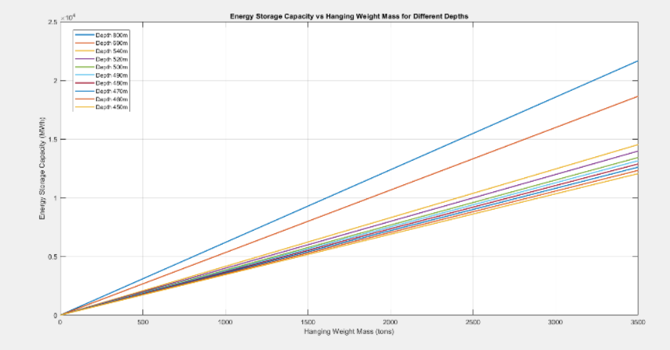

Fig. 5. Energy storage capacity of the British mines based on the mines and quarries database [18].

According to the database of mines and quarries there are 11 deep abandoned mines in Britain [9] but only a few mines in Britain go beyond 500 meters in depth, and all those mentioned have depths greater than 400 meters[18]. Given this, and considering the graph's pattern, it seems reasonable to establish a baseline storage capacity of 1 MWh at a depth of 400 meters for the mines listed in the database. This choice aligns with the actual mining depths found in the data and ensures practical feasibility for these specific mines in Britain as shown in figure 5.

The inclusion of two abandoned mines in the dataset, boasting depths of 690 and 800 meters respectively, introduces intriguing possibilities for enhanced energy storage. These greater depths signify a potential for increased energy capacity compared to shallower mines. Considering the consistent weight of 3500 tonnes across both scenarios, these abandoned mines may hold the promise of higher energy storage capabilities, leveraging the deeper depths to optimize gravitational potential energy utilization. This opens avenues for exploring more significant energy storage solutions in these abandoned mines. The graph clearly shows that these two mines have capacity more than 2MWh with 3500 tonnes.

B. *Result of Mineshaft Gravity battery integrate with Britain’s Grid*

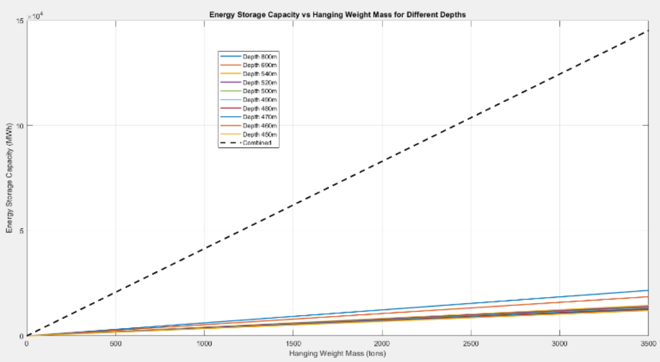

Fig. 6. Graphical Representation of Britain's Mineshaft Storage Capacities, the dotted lines represent the unifying potential of storage capacities.

To fully evaluate the integration of mineshaft gravity batteries into the grid, it's crucial to view these mines as an interconnected system. This approach enables a detailed examination of the integration's possibilities and challenges, considering the collective impact and synergy of the mines within the grid infrastructure.

Figure 7 describes gravity battery as a solution for daily peak demand and demand side management.

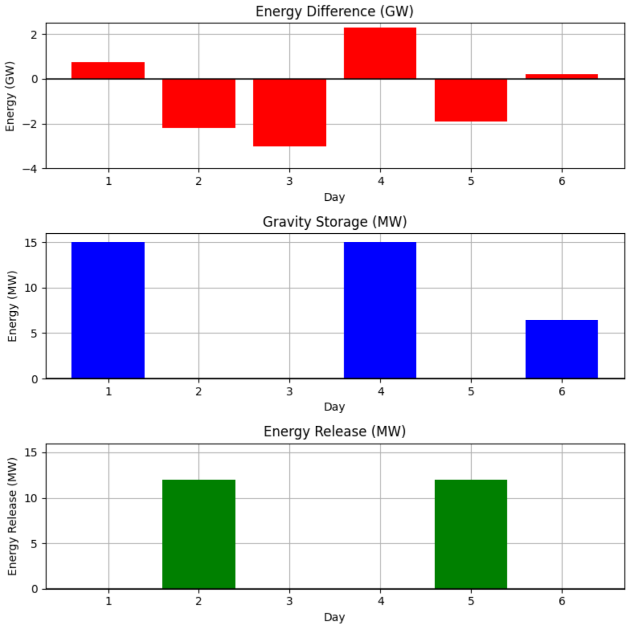

Fig. 7. The graph illustrates the daily peak demand and the implementation of demand side management, incorporating the use of a gravity battery, utilizing data from Britain's national grid [19].

The first graph shows daily energy dynamics in Britain, highlighting surpluses when production exceeds demand. The second graph focuses on the gravity battery's role in managing surplus energy, accumulating up to 15 MWh for later use. No energy release is needed on surplus days like the first, emphasizing the system's efficiency in storing excess energy for future use.

On the second day, as demand exceeds production, the gravity battery releases stored energy until reaching maximum capacity, demonstrating its adaptive nature. However, on the third day, despite demand surpassing production, no additional energy is released because the battery reached its maximum limit the day before, highlighting its finite capacity and real-time adaptation to grid demands.

On the fourth day, the gravity storage system accumulated surplus energy up to its maximum capacity, releasing it on the fifth day to meet increased demand. On the sixth day, energy production fell short of maximum storage capacity, resulting in partial storage. The system utilizes 15 MWh for storage and releases only 80% of stored energy. This highlights the potential for enhancing energy demand fulfilment by integrating the gravity battery with other storage systems, leveraging their combined capacities for a robust energy infrastructure. Integrated storage systems hold the key to efficiently meeting evolving energy needs.

C. *Result for Harnessing Mineshaft Gravity Battery with Wind energy generation*

The first graph emphasizes wind energy's importance in meeting demand. The second graph outlines the efficiency of gravity battery storage. The third graph shows direct wind energy transfer to meet demand without using gravity battery storage. The fourth graph highlights days when the gravity battery releases stored energy to fulfil demand, demonstrating its strategic role in managing energy supply dynamics.

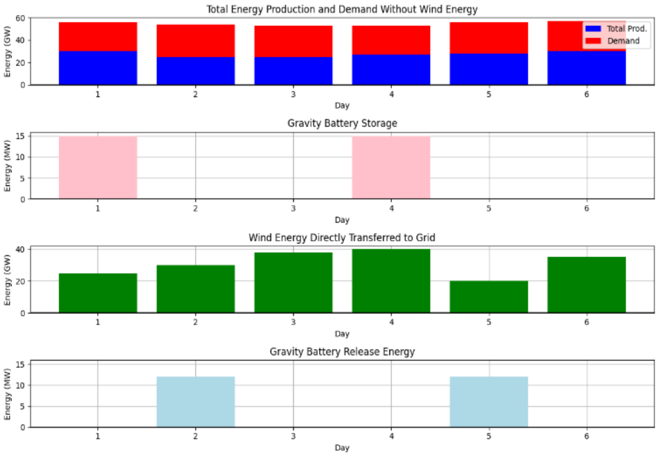

Fig. 8. This series of graphs illustrates the operational dynamics of a gravity battery seamlessly incorporated within the interface of the grid and wind energy generation.

On the first day, surplus wind energy (approx. 15MW) is stored in the gravity battery to meet demand. On the second day, despite wind energy, the battery releases 80% of stored energy to address demand shortfalls [20]. On the third day, demand exceeds available energy, depleting gravity storage. On the fourth day, surplus wind energy is maximized and stored in the gravity battery. On the fifth day, stored energy efficiently meets demand, showcasing the system's dynamic response. While a standalone 15MW gravity storage system from abandoned mines might not fully meet Britain's energy demand, its integration into the broader infrastructure significantly boosts storage capabilities. By utilizing energy stored in abandoned mineshafts, the gravity battery system enhances resilience and capacity to manage energy fluctuations. This integrated approach exemplifies the synergistic effect of diverse energy sources, creating a robust storage system for Britain's demands.

The gravity battery system addresses wind curtailment by strategically storing excess energy, preventing production reduction due to grid surplus. Increasing gravity storage capacity can notably reduce curtailment, enhancing system flexibility and optimizing renewable energy distribution for sustainability.

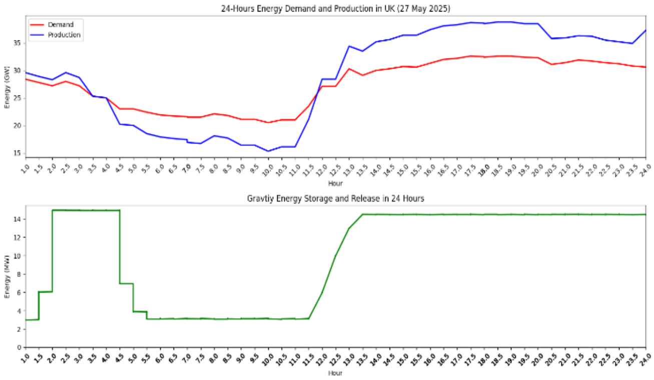

Fig. 9. The graph above illustrates the 24-hour energy demand and production in the UK and demonstrates how gravity storage responds to fluctuations.

The graph illustrates the interaction between energy demand, production, and gravity energy storage over a 24-hour period in the UK. It shows that during periods when energy production exceeds demand, the gravity storage system actively stores the surplus energy, leading to an increase in stored capacity. Conversely, when demand surpasses production, the system transitions to a release phase, discharging stored energy to help meet the shortfall. This dynamic operation demonstrates the effectiveness of gravity-based storage in stabilising the grid by absorbing excess energy and supplying power during peak demand, thereby enhancing overall energy efficiency and reliability.

V. FUTURE SCOPE

Britain's commitment to a net-zero carbon economy drives a revolution in energy storage, with mineshaft gravity batteries offering scalable, high-capacity storage of up to 15 MWh. This integration enhances storage capabilities, balancing renewable energy fluctuations effectively.

Repurposing abandoned mines as gravity battery sites innovatively utilizes existing infrastructure, minimizing environmental impact and transforming idle spaces into assets that enhance national energy resilience.

Mineshaft gravity batteries complement renewable energy variability, smoothing out production fluctuations and ensuring a reliable energy supply. They store excess energy during high production periods and release it during lulls, stabilizing the grid and mitigating the impact of renewable energy variability.

Mineshaft gravity batteries mitigate wind curtailment by storing excess energy during surplus periods and releasing it during high demand or low wind output, ensuring efficient utilization and reducing renewable power wastage.

Mineshaft gravity batteries enhance grid resilience by providing fast-reacting power and system balancing capabilities, crucial as coal assets are phased out. They efficiently fill gaps, supporting grid stability during high demand or low renewable energy output periods. This kind of energy storage can also work for co-optimization of energy storage and reserve as in [21].

VI. CONCLUSION

This paper explores integrating mineshaft gravity batteries into Britain's energy landscape, revealing a promising avenue for sustainable solutions. Investigating storage capacity highlighted the critical depth-weight relationship for achieving 1 MWh capacity, emphasizing the practicality of repurposing abandoned mines for enhanced energy storage.

The synergy between mineshaft gravity batteries and wind energy optimizes energy availability during peak periods. While the battery's capacity alone may be insufficient for comprehensive energy demands, its strategic utilization in dynamic scenarios underscores its pivotal role in managing supply and demand fluctuations.

The exploration of mineshaft gravity batteries as a sustainable energy solution for Britain charts a transformative path forward, repurposing abandoned mines to enhance energy storage capacities and address wind curtailment. While acknowledging limitations, the findings advocate for their pragmatic incorporation into a diversified energy portfolio, contributing to Britain's aspirations for a resilient, sustainable, and environmentally conscious energy future.

REFERENCES

[1] EU-SysFlex, “Energy storage: Key to the effective use of renewables?” *EU SYSFLEX*, Feb. 22, 2022. Available online: https://eu-sysflex.com/energy-storage-key-to-the-effective-use-of-renewables/

[2] Marlow, “Material Properties,” *Marlow Ropes*, 2023. Available Online: https://www.marlowropes.com/innovation/material-properties/

[3] National Grid Group, “How much of the UK’s energy is renewable? | National Grid Group,” 2023. Available online: https://www.nationalgrid.com/stories/energy-explained/how-much-uks-energy-renewable

[4] N. Chatrung, “Battery Energy Storage System (BESS) and Development of Grid Scale BESS in EGAT,” *2019 IEEE PES GTD Grand International Conference and Exposition Asia*. DOI: 10.1109/GTDAsia.2019.8715953

[5] A. Rogers, A. Henderson, X. Wang, and M. Negnevitsky, “Compressed air energy storage: Thermodynamic and economic review,” *2014 IEEE PES General Meeting*

[6] X. P. Nguyen and A. T. Hoang, “The Flywheel Energy Storage System: An Effective Solution to Accumulate Renewable Energy,” *2020 6th International Conference on Advanced Computing and Communication Systems (ICACCS)*

[7] International Hydro Power, “International Hydropower Association,” *www.hydropower.org*, 2022. Available online: https://www.hydropower.org/factsheets/pumped-storage

[8] M. Aneke and M. Wang, “Energy storage technologies and real-life applications – A state of the art review,” *Applied Energy*, vol. 179, pp. 350–377, Oct. 2016, doi: https://doi.org/10.1016/j.apenergy.2016.06.097.

[9] R. BOWELL, “The United Kingdom Has Thousands of Abandoned Metal Mines | SRK Consulting,” *www.srk.com*, 2023. Available online: https://www.srk.com/en/publications/the-united-kingdom-has-thousands-of-abandoned-metal-mines

[10] P. Fraenkel and M. Wright, “Apparatus and method for electrical energy storage,” *Google Patents*, Sep. 26, 2019. https://patents.google.com/patent/GB2509437A/en

[11] A. C. Ruoso, N. R. Caetano, and L. A. O. Rocha, “Storage Gravitational Energy for Small Scale Industrial and Residential Applications,” *Inventions*, vol. 4, no. 4, p. 64, Oct. 2019, doi: https://doi.org/10.3390/inventions4040064

[12] S. Butler, “What Are Gravity Batteries, and How Do They Work?” *How-To Geek*, Nov. 06, 2022. Available online: https://www.howtogeek.com/839512/what-are-gravity-batteries-and-how-do-they-work

[13] Offshore, “Yantai Raffles’ world-record gantry crane should see first lift this year,” *Offshore*, Jun. 01, 2008. https://www.offshore-mag.com/vessels/article/16761633/yantai-raffles-worldrecord-gantry-crane-should-see-first-lift-this-year

[14] XINGYNG, “Steel Wire Ropes for All Types of Elevators,” *www.steelwirerope.org*, 2020. https://www.steelwirerope.org/steelwirerope/elevator-wire-rope.html

[15] T. Morstyn, M. Chilcott, and M. D. McCulloch, “Gravity energy storage with suspended weights for abandoned mine shafts,” *Applied Energy*, vol. 239, pp. 201–206, Apr. 2019, doi: https://doi.org/10.1016/j.apenergy.2019.01.226

[16] P. Fraenkel and M. Wright, “Apparatus and method for electrical energy storage,” *Google Patents*, Sep. 26, 2019. https://patents.google.com/patent/GB2509437A/en

[17] M. Akmal, D. Flynn, J. Kennedy and B. Fox, "Flexible heat load for managing wind variability in the Irish power system," *2009 44th International Universities Power Engineering Conference (UPEC)*, Glasgow, UK, 2009,

[18] B. G. Survey (BGS), “Mines and Quarries Database - BritPits.,” *www.data.gov.uk*, Nov. 09, 2023. https://www.data.gov.uk/dataset/8c660338-8721-4274-bd90-c53aa909104a/mines-and-quarries-database-britpits

[19] K. R. Morley, “National Grid: Live Status,” *grid.iamkate.com*, 2022. https://grid.iamkate.com/

[20] Official Website of the International Trade Administration, “United Kingdom Energy Storage Market,” *www.trade.gov*, Jun. 10, 2021. Available online: https://www.trade.gov/market-intelligence/united-kingdom-energy-storage-market.

[21] M. W. Hassan, M. B. Rasheed, N. Javaid, W. Nazar, and M. Akmal, "Co-optimization of energy and reserve capacity considering renewable energy unit with uncertainty," *Energies*, vol. 11, no. 10, 2018. pp. 2833