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DEVELOPMENT OF A CONCEPT OF GRAVITY ENERGY STORAGE SYSTEMS BASED ON DISCONTINUED WELLS

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The object of the study is the well gravity energy storage system (WellGES) implemented in a vertical oil and gas well. The system consists of a heavy load suspended on steel cables that moves along the shaft of a discontinued well to convert potential energy into electrical energy via generators. The inherent instability of renewable energy sources requires the implementation of grid balancing technologies and peak load coverage.

A concept is proposed that involves using the great depth of decommissioned oil and gas wells for gravity energy storage, as well as the feasibility of using such technology for large-scale energy storage.

The well gravity energy storage system converts excess electrical energy into potential mechanical energy. This conversion is carried out by lifting a load-storage unit that moves freely along the wellbore using a cable and a drum with an electric machine operating in engine mode. When the load is lowered, the electric machine switches to regenerative braking mode, returning the stored energy to the power grid.

The advantages of the well gravity energy storage system over existing similar systems have been identified. In particular, the use of a significant height difference (deep wells), lower capital investments due to the use of ready-made objects, environmental safety, and independence from atmospheric conditions. Kinematic and power calculations of the system are carried out, including determining energy consumption, calculation of the hoist, selection of an electric machine and gear ratio of a multi-stage mechanism. Using the example of well No. 64 – Dolyna (depth 2000 m, load 4000 kg), it was calculated that the battery capacity is 22 kWh, which confirms the possibility of implementing the system

Keywords: gravity energy storage, wells, renewable energy sources, load-storage unit

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1. Introduction

Global industrialization, urbanization, and population growth are having a significant impact on ecosystems and living conditions, increasing the demand for energy, mostly of fossil origin. This is stimulating the rapid expansion of installed capacity of wind and solar power plants, which effectively reduce dependence on fossil fuels and reduce CO_2 emissions from their combustion. However, the increase in the share of renewable energy sources (energy sources – RES) (solar and wind) in distribution networks, as well as load instability, cause a number of problems: peak power drops, voltage fluctuations, reverse currents, etc. Energy storage systems (ESS) are a key solution to overcome them and are widely used in modern energy networks.

One of the most promising areas is gravitational energy storage, which is based on the conversion of potential energy of masses in a gravitational field into electrical energy. Gravitational storage systems are one of the most promising technologies for large-scale energy storage. They combine reliability, long-term resource, economic feasibility and high environmental sustainability, having advantages over battery systems and better geographical adaptability compared to traditional pumped storage power plants. The last decade is characterized by a rapid growth of scientific interest in this technology, which is confirmed by technical and economic research.

One of the important parameters of gravity storage systems is the height to which the load is moved, increasing which will lead to a proportional increase in the stored potential energy. This will allow to increase the capacity of the system without significantly increasing the mass of the load, improving the overall efficiency (efficiency) and cost-effectiveness for long-term storage. In well systems, the depth can reach several thousand meters, which makes such installations competitive with traditional pumped storage power plants.

The number of old liquidated or decommissioned oil and gas wells in Ukraine reaches thousands of units, about 4,000 according to the example of Ukrnafta, with a significant share of wells in various states of liquidation or resuscitation.

Thus, the scientific issue of gravitational energy storage remains extremely relevant in the context of the global energy transition, where the need for sustainable, large-scale and environmentally friendly solutions for storing excess renewable energy is constantly growing. Further study, in particular the adaptation of the technology to decommissioned and liquidated oil and gas wells, opens up new opportunities for integration into energy systems, contributing to decarbonization and energy security.

2. Literature review and problem statement

In [1], an analysis of gravitational energy storage (GES) is presented, which shows that pumped storage power plants have reached a high level of maturity as a technical system and are well covered by economic evaluation methods, while solid-state GES are still at the initial stage of system design and evaluation. The development and improvement of integration methods between various renewable energy sources and GES are key areas for future development.

GES demonstrates high cyclic efficiency (80–90%), scalability to several GWh , and good geographical adaptability [2]. Among solid-state GES systems, tower, rail, mine, and mountain systems are distinguished, while liquid analogues in the form of pumped storage plants (PHES) remain the most developed. One of the significant disadvantages of PHES is that it depends on the topography and the slight difference in altitude levels in which the energy storage device is moved [3]. The use of bulk materials (MGES) opens up prospects for isolated networks, providing storage costs at the level of $50–100/MWh [4]. However, the influence of external factors, such as precipitation, makes it seasonal.

The competitiveness of GES is determined by the cost in eurocents/kWh compared to PHES, compressed air systems (CAES) and lithium-ion batteries. Levelized energy cost (LCOS) for classic systems is 7.5–15 eurocents/kWh, and for solutions based on cable hoists – only 3.8–7.3 eurocents/kWh [5]. This makes GES an attractive alternative, especially considering the long service life and low operating costs. Financial models using internal rate of return (IRR), net present value (NPV), annual debt coverage ratio (ADSCR) and the debt coverage ratio for the entire loan term (LLCR) demonstrate the investment feasibility of such systems. For a facility with a capacity of 1 GW and a capacity of 125 MWh, the calculated LCOS was only 202 USD/MWh [6, 7].

The technical implementation of GES includes the use of drum lifts, multi-piston systems and linear electric machines [8]. Traditional lifts provide reliability, while linear machines open up the prospect of high energy density and fast regulation. Some studies suggest integration with renewable sources, such as solar -gravity systems, where RES energy is used to lift loads [9]. Synergy of GES with wind and photovoltaic stations is considered as one of the key areas of development. Optimization algorithms allow to reduce the required capacity by 30–35%, increasing economic efficiency compared to battery systems [10]. Development trends are aimed at creating hybrid gravity energy storage systems (hybrid gravity energy storage – HGES), which combine gravity storage and supercapacitors. This provides both long-term and ultra-fast energy storage, increasing the flexibility of electrical networks [11].

The concepts of placing energy storage systems directly in cities are promising. One of these is the technology of urban energy storage based on elevator systems in high-rise buildings (LEST). They provide storage potential up to 30–300 GWh , and the cost of installed capacity varies within 21–128$/kWh [12]. The disadvantage of LEST is the relatively high cost and the small difference in height levels in which the storage load is moved.

At the same time, there are challenges to implementing GES: high capital costs, difficulty in optimizing lifting mechanisms, losses during conversion, as well as restrictions due to the relief [3]. The lack of unified methods of economic assessment complicates the prediction of commercialization [13]. However, SWOT analysis indicates the most promising markets – countries with a high share of RES, regions with abandoned mines, large cities and isolated power systems [2, 4, 12].

Practical implementation is confirmed by a number of projects . The most famous are the developments of Energy Vault in Switzerland and China, which involve lifting concrete blocks using cranes. The efficiency of such systems reaches 80–85%, and the capacity is tens of MWh [14]. In addition to the advantages, the technical problem is the complexity of controlling many drives, the need to create a basic infrastructure that requires significant capital investments, as well as a small difference in the height levels in which the storage load is moved. Another example is Gravitricity systems , which use loads weighing 50 tons in vertical shafts. They provide an ultra-fast response, which makes them suitable for frequency control in the network [15]. However, the use of shafts is limited by the difference in height in which the storage load is moved. A promising alternative is advanced rail energy storage (ARES), where electrified cars move along slopes, accumulating and releasing energy. Tests have confirmed the possibility of creating systems with a capacity of 50 MW with a discharge time from 15 minutes to several hours [16]. However, the application of ARES is limited by requirements for the terrain, the construction of basic infrastructure, a slight difference in altitude, the influence of atmospheric factors, and a significant length on the surface of the earth.

Based on the above, it can be noted that modern solid-state gravitational energy storage systems have a number of disadvantages. Firstly, the storage loads move in the range of minor differences in height levels, which limits energy intensity. Secondly, the construction of the basic infrastructure and complex design entails significant time and money costs, complicates maintenance and operation. Thirdly, the negative impact of atmospheric precipitation (rain, ice, and especially snow) on the operation of GES. Fourthly, a significant length on the surface of the earth, which makes them easy targets in the event of air strikes, which is currently especially relevant.

So, summing up the above, it is possible to conclude that one of the further ways to improve GES is: increasing the height difference; reducing capital investments in their arrangement and maintenance; ensuring accessibility and scalability. In the future, this will increase the economic attractiveness of GES and accelerate their commercialization, which contributes to decarbonization and energy security.

3. The aim and objectives of the study

The aim of the study is to develop a concept and assess the technical and economic parameters of gravity energy storage (WellGES) based on decommissioned wells to ensure effective long-term storage of excess electricity, stabilization of power grids and integration with renewable sources. This objective focuses on the rational use of existing oil and gas industry infrastructure, in particular decommissioned wells, as potential shafts for lifting/lowering cargo, converting potential gravitational energy into electrical energy.

The specified aim is achieved by solving the following objectives:

– design a structural diagram of a WellGES;

– calculate the energy consumption of the system;

– determine the parameters of the functional parts of the mechanical transmission for converting potential energy into electrical energy and vice versa.

4. Materials and methods

The object of the study is a WellGES implemented in a vertical shaft of an oil and gas well. The system consists of a heavy load (made of concrete or steel) suspended on steel cables, which moves along the shaft to convert potential energy into electrical energy using generators. The main hypothesis of the study is that the WellGES well system based on a decommissioned well achieves an energy storage efficiency of 70–85% in cyclic charge/discharge modes. It surpasses traditional batteries in terms of durability (over 30 years of service) and environmental friendliness, providing an economic payback of less than 10 years at an energy cost below 0.05 USD/kWh.

The following assumptions were made in the study:

– the well has a stable barrel geometry (diameter 0.2–0.3 m) without significant deformations, with waterproofing that can withstand pressure up to 50 MPa;

– the load moves without significant friction (friction coefficient < 0.05) thanks to lubricants or roller systems; energy losses due to thermal and vibration loads do not exceed 10–15% of the total cycle;

– access to the power grid is provided by standard capacity of 1–10 MW for scalability.

At the same time, the study methodology is based on a systematic approach to developing the concept of a downhole gravity energy storage system. The study is based on methods of theoretical analysis, mathematical modeling of physical processes, and engineering calculations of mechanical systems.

To determine the energy potential of the system, classical equations of physics and mechanics were used.

The method of kinematic-force analysis was used to calculate the multistage gear mechanism . This approach allows determining the gear ratios and powers on each shaft in the gearbox and multiplier modes [17].

Validation process of the proposed solutions was carried out by checking the energy capacity matching condition. The calculated values of the capacities on the drum were compared with the characteristics of the electric machines using catalog data [17].

The calculations were carried out using the characteristics of the decommissioned well No. 64 – Dolyna. The geometric dimensions of the wellbore are as follows: length of the straight section – 2000 m, diameter – 219 mm.

The construction of the structural diagram was carried out using specialized computer modeling software AutoCAD, manufactured in the USA. The Canadian application for engineering calculations Waterloo was used to perform calculations related to mechanical transmission Maple .

5. Results of research on a well gravity energy storage system

5. 1. Design of a structural diagram of the well gravity energy storage

The proposed concept of gravity-based energy storage consists in using decommissioned oil and gas wells as storage tanks, as well as a vertical shaft and electric motors/generators for lifting and lowering the load. The schematic diagram of the proposed device is shown in Fig. 1. The well gravity energy storage (Fig. 1) is installed at the wellhead 1. The mounted energy conversion module 2 contains a drum 3 with a traction cable 4 wound on it, a pulley 5, a brake 6, a clutch 7, a multi-stage gear mechanism 8 and an electric machine 9 with a connection to an external power grid 10. A storage load 11 is installed in the well, which is connected to the traction cable 4.

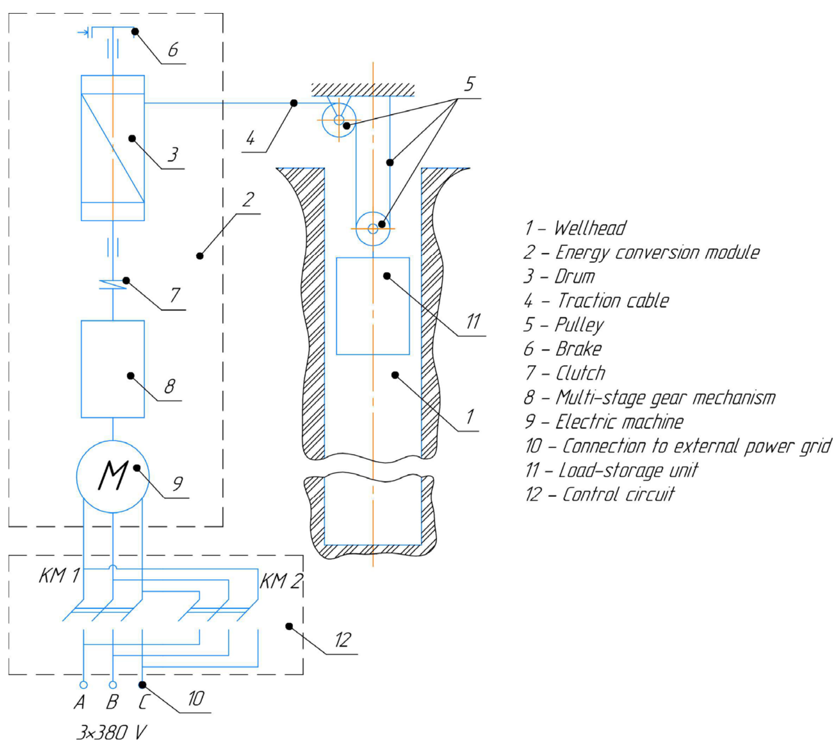

Fig. 1. Structural diagram of the well gravity energy storage system

The electric machine 9 operates in the electric motor mode when lifting the load-accumulator 11, and in the electric generator mode when lowering the load-accumulator 11. The lifting and lowering process is selected by the control circuit 12.

The proposed device uses the well-known principle of converting the potential energy of the load-storage unit 11 into kinetic energy, and vice versa. In the uppermost position, the load-storage unit 11 becomes a carrier of potential energy, which in a gravitational field can again be converted into kinetic energy, and after the appropriate conversion - into electrical energy.

WellGES works as follows. The electricity generated by external sources is supplied to the electric machine 9 through the control circuit 12. The motor mode of the latter is switched on by closing the contactor KM1 (Fig. 1). At the same time, the load-storage unit 11 is raised to accumulate potential energy. The generator mode is provided by closing the contactor KM2. At the same time, the load-storage unit 11 is lowered, which is accompanied by the production of electricity, which is fed into the power grid, where it is consumed.

Thus, the incoming electrical energy from external energy sources is accumulated in the form of mechanical potential energy, integrated, and then converted back into electric current. The latter is already standardized in frequency and voltage so that it can be used by consumers.

5. 2. Calculation of system energy consumption

The potential energy that the storage load will store is determined by the well-known formula

$$U = mgh = V\rho gh, \tag{1}$$

where m, V, ρ – the mass, volume, and density of the storage load material;

g – the acceleration due to gravity.

Weight of the accumulator load

$$G_B = mg. \tag{2}$$

The speed of movement of the storage load along the well is calculated according to the following equality

$$\upsilon = \frac{h}{t}, \tag{3}$$

where h – the length of the well section within which the accumulator load is moved;

t – the time during which the distance h is covered.

The value of h depends on the well design. It is recommended to choose a straight, conditionally vertical section of the shaft for greater efficiency of the system. Time t should be coordinated with the period when there is a surplus of electrical energy that should be accumulated. Or with the required power that WellGES will provide during its release.

The power developed by the storage load when moving

$$W = G_B\upsilon. \tag{4}$$

Therefore, the energy intensity of WellGES in $W \times h$ is equal to

$$E = \frac{Wt}{3600}. \tag{5}$$

The WellGES installation in the decommissioned well No. 64 – Dolyna was calculated. It was found that the potential energy accumulated by the storage load under such operating conditions is 78 MJ. Assuming that the period of both storage and release of electrical energy will be 6 h, the capacity of the gravity storage will be 22 kWh . Based on the geometric dimensions of the well: a straight section of the shaft with a length of 2000 m and a diameter of 219 mm – a storage load with a mass of 4000 kg, a diameter of 180 mm and a length of 20 m was used for the calculation.

5. 3. Calculation of functional parts of mechanical transmission for converting potential energy into electrical energy and vice versa

The efficiency of a pulley block can be obtained by the formula [17]

$$\eta_P = \frac{\left(1-\eta_{BL}^n\right)\eta_{BL}^n}{\left(1-\eta_{BL}^n\right)i_P}, \tag{6}$$

where $\eta_{BL}^n = 0.98$ – the efficiency of one unit on rolling bearings;

n – the number of bypass and guide blocks;

i_P – the multiplicity of the pulley block, which is equal to the ratio of the number of branches of the traction device on which the load is suspended to the number of branches of the traction device that run onto the drum.

The next step is to determine the standard size of the hook suspension, which depends on the multiplicity of the block and the nominal load capacity of the standard hook suspension Q_{HS}^H, which must be greater than or equal to the weight of the load Q_B (or G_B) [17]. Also, the diameter of the suspension block along the bottom of the groove should be fixed $D_{BL.O}^{HS}$

$$Q_{HS}^H \geq Q_B. \tag{7}$$

In addition, from [17] one should choose the range of rope diameters that can be used for this suspension. Thus, the maximum static rope tension force is determined according to the formula

$$F_{ST.\mathrm{MAX}} = \frac{G_B + G_P}{z_B i_P \eta_P}, \tag{8}$$

where z_B – the number of strands of the traction rope that run onto the drum;

G_P – weight of the hook suspension.

Next, the calculated breaking force of the rope is calculated [17]

$$F_{BF} = KF_{ST.\mathrm{MAX}}, \tag{9}$$

where K – the safety factor selected according to the table.

The rope size is selected from table [17], applying the breaking strength condition

$$F_{B.R} \geq F_{B.F}, \tag{10}$$

where F_{BR} – the closest tabulated value of the rope breaking force.

The selected rope should be tested for durability and evenness

$$D_{BL.O}^C \leq D_{BL.O}^{HS}, \tag{11}$$

where $D_{BL.O}^C$ – the calculated value of the diameter of the hook suspension block along the bottom of the groove.

The value $D_{BL.O}^P$ is determined by the formula [17]

$$D^C_{BL.O} = ed_K - d_K, \quad (12)$$

where e – a coefficient that depends on the type of crane and operating mode;

d_K – diameter of the selected rope size.

The calculated diameter of the drum is determined along the midline of the rope [17]

$$D^c_D = 0.85ed_K. \quad (13)$$

Next, the estimated diameter of the drum along the bottom of the screw groove is calculated

$$D^C_{BO} = D^C_D - d_K. \quad (14)$$

The value D^C_{BO} is consistent with the standard value of the drum diameter along the bottom of the helical groove D^s_{BO}. Therefore, the specified value of the drum diameter along the center line of the rope

$$D^s_D = D^s_{BO} + d_K. \quad (15)$$

Next, the calculation is made taking into account the fact that a rope of considerable length will have to be wound onto the drum. This means that the laying process will take place in several layers. It is obvious that the rope will be wound onto the drum in the form of Archimedean spirals (Fig. 2), which are placed next to each other.

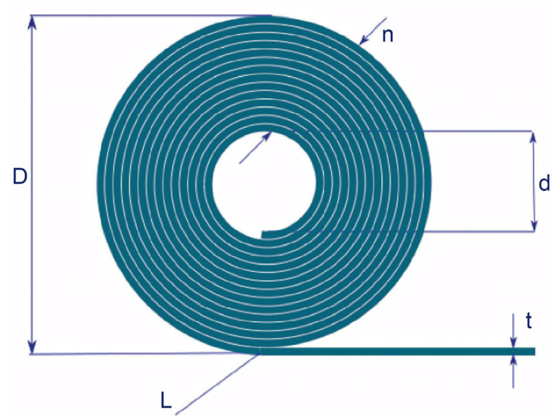

Fig. 2. The rope is laid in an Archimedean spiral

The value of the inner diameter of the spiral is taken to be equal to D^S_D. The value of the outer diameter of the drum together with the wound rope is denoted by D^{max}_d. This value is chosen based on design considerations. The initial and final angles of the spiral are calculated as follows:

$$\phi_0 = \frac{\pi D^s_D}{d_K}, \quad \phi_1 = \frac{\pi D^{max}_D}{d_K}. \quad (16)$$

The number of turns of the spiral provided that its outer diameter reaches the value D^{max}_d

$$n_t = \frac{\phi_1 - \phi_0}{2\pi}. \quad (17)$$

In this case, the length of the rope, which corresponds to one Archimedean spiral with the number of turns n_t, can be determined by the formula

$$L = \frac{d_K}{2\pi}\left(\begin{array}{l} \frac{\phi_1}{2}\sqrt{\phi_1^2+1} + \frac{1}{2}\ln\left(\phi_1 + \sqrt{\phi_1^2+1}\right) - \\ -\frac{\phi_0}{2}\sqrt{\phi_0^2+1} - \frac{1}{2}\ln\left(\phi_0 + \sqrt{\phi_0^2+1}\right) \end{array}\right). \quad (18)$$

Then, the number of Archimedean spirals needed to wind the entire rope is equal to

$$n_s = \frac{hi_P}{L}. \quad (19)$$

Therefore, the total length of the drum is

$$l_s = n_s d_K. \quad (20)$$

Based on the above analytical dependencies and taking into account the initial value of the drum diameter, which is 215 mm, the dynamics of changes in its geometric parameters during operation was established. As a result of the complete winding of the calculated length of the rope, the final diameter of the system increased to 1250 mm. Such an increase in diameter indicates a significant multi-layered laying. This fact requires additional consideration when calculating the torque and traction force on the drive, which in turn affects the speed of movement and the load of the electric motor.

The power that must be developed by the drum to lift the storage load is determined as follows

$$W_D = \frac{W}{\eta_L}. \quad (21)$$

Therefore, according to Fig. 3, the calculated power of the electric machine is equal to

$$W^C_{DG} = \frac{W_D}{\eta_{MSM}}, \quad (22)$$

where η_{MSM} – the efficiency of the multi-stage gear mechanism.

An electric machine with a rated power equal to or greater than the value is selected from the catalog W^c_{DG}.

In general, as can be seen from Fig. 1, a pulley block with a multi-stage gear mechanism is used to coordinate the parameters of the movement of the load-accumulator and the rotor of the electric machine. Therefore, the angular velocity of the drum shaft, taking into account that the linear velocity of the load-accumulator movement along the well is less by i_P times than the linear velocity of the rope strand approaching the drum, is calculated as follows

$$\omega_B = \frac{2i_P\upsilon}{D^{max}_D}. \quad (23)$$

Angular speed of the rotor of the selected electric machine

$$\omega_{DG} = \frac{\pi n_{DG}}{30}, \quad (24)$$

where n_{DG} – the rotor speed of the electric machine.

Therefore, the calculated gear ratio of a multi-stage gear mechanism is determined by the formula

$$u^c_{MSM} = \frac{\omega_{DG}}{\omega_D}. \quad (25)$$

Next, a multi-stage gear mechanism with an equal or the nearest larger gear ratio u_{BZM} is selected from the catalog. One of the main functional features of a multi-stage gear mechanism is the need to operate in both the reducer and multiplier modes. In view of this, it is recommended to choose cylindrical gears as the stages. It is assumed to use 3 stages (Fig. 3).

The gear ratio can also be expressed as

$$u_{MSM} = u_{23} u_{34} u_{45}, \tag{26}$$

where u_{23}, u_{34}, u_{45} – the gear ratios of gears between shafts 2 and 3, 3 and 4, 4 and 5, respectively.

Then, the efficiency of a multi-stage gear mechanism will be determined by the formula

$$\eta_{MSM} = \eta_C^2 \eta_{PB}^5 \eta_G^3, \tag{27}$$

where η_c – the coupling efficiency;

η_{PB} – efficiency of a pair of bearings;

η_G – gear efficiency.

Taking this into account, the kinematic-force analysis of the drive is conveniently presented in the form of Table 1.

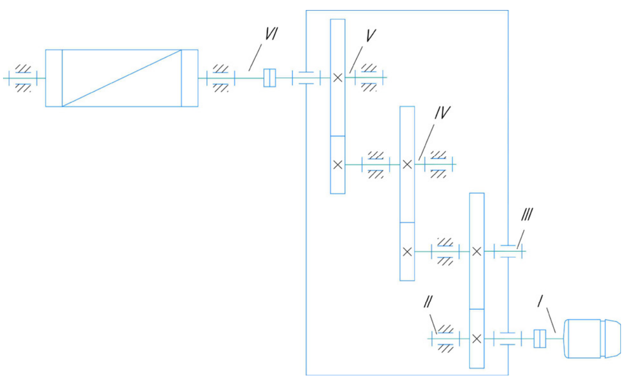

Fig. 3. Scheme of a multi-stage gear mechanism

Table 1

Kinematic and force calculations of a multi-stage gear mechanism

Shaft No.	n, rpm	ω, rad/s	P, W	T, Nm
I	$n_I = n_{DG}$	$\omega_I = \omega_{DG}$	$P_I = W_{DG}^c$	$T_I = P_I / \omega_I$
II	$n_{II} = n_I$	$\omega_{II} = \omega_I$	$P_{II} = P_I \eta_C \eta_{PB}$	$T_{II} = T_I \eta_C \eta_{PB}$
III	$n_{III} = n_{II} / u_{23}$	$\omega_{III} = \omega_{II} / u_{23}$	$P_{III} = P_{II} \eta_{GE} \eta_{PB}$	$T_{III} = T_{II} \eta_{GE} \eta_{PB} u_{23}$
IV	$n_{IV} = n_{III} / u_{34}$	$\omega_{IV} = \omega_{III} / u_{34}$	$P_{IV} = P_{III} \eta_{GE} \eta_{PB}$	$T_{IV} = T_{III} \eta_{GE} \eta_{PB} u_{34}$
V	$n_V = n_{IV} / u_{45}$	$\omega_V = \omega_{IV} / u_{45}$	$P_V = P_{IV} \eta_{GE} \eta_{PB}$	$T_V = T_{IV} \eta_{GE} \eta_{PB} u_{45}$
VI	$n_{VI} = n_{IV}$	$\omega_{VI} = \omega_{IV}$	$P_{VI} = P_{IV} \eta_S \eta_{PB}$	$T_{VI} = T_{IV} \eta_S \eta_{PB}$

It should be noted that for the operation of a borehole gravity energy accumulator, the following condition must be met

$$T_{VI} \geq 0.5 D_D^{\max_{ST.MAX}}. \tag{28}$$

To ensure the fulfillment of this condition, the following results were obtained regarding the coordination of the parameters of the movement of the load-accumulator and the rotor of the electric machine (asynchronous electric motor AIR160M6, power – 15 kW; rotor speed – 970 rpm; nominal torque on the rotor – 148 N×m) a 4-fold pulley with a three-stage cylindrical gearbox CZU-400 is used (gear ratio – 200, nominal torque on the low-speed shaft – 20 kN×m).

6. Discussion of the results of the developed concept of a well gravity energy storage system

A feature of the proposed concept of a well gravity energy storage system is using the shaft of liquidated or decommissioned wells to move cargo over long distances, which will increase the efficiency of the system due to minimal energy losses and scalability, while reducing capital costs for infrastructure. This will allow the integration of abandoned oil or gas wells into new energy projects , increasing the profitability of gravity storage. This approach also contributes to the stabilization of the power grid through long-term storage of potential energy without significant wear and tear on the equipment.

WellGES energy storage system solves the problem of small height differences, typical for most ground-based GES systems, without the need to build special pits or high structures. For example, the GES constructed Gravitricity is tens of meters [15]. At the same time, Energy Vault is building a GES hundreds of meters high [14]. The proposed WellGES concept has a height difference of several thousand meters. The system is based on the reuse of existing infrastructure, namely decommissioned wells. The use of existing wells (1000–3000 m deep) reduces capital costs compared to new mines or towers Gravitricity/Energy Vault [14, 15]. The key factor that ensures significant energy consumption of the system is the use of a large difference in the height of the load movement (2000 m and more). Since the multiplicity of the pulley block is 4, which implies a significant length of the rope, an important feature is the calculation of the dynamics of the rope winding according to the principle of the Archimedes spiral. The location of the main components – an electric machine, a gearbox and a brake – on the ground surface (Fig. 1) simplifies maintenance and repair, which directly increases the reliability and durability of the system.

WellGES technology provides the possibility of linear scaling of energy capacities by involving the existing well fund of the field, which can reach dozens of units. Each individual well acts as an independent unit of energy storage, which allows to increase the capacity without radical changes in the engineering infrastructure. The total energy intensity of such a system is calculated as an additive value, which is directly proportional to the number of integrated WellGES units. Another way of scaling is to increase the mass of the cargo. Thus, by increasing the mass of the cargo to 10,000 kg and involving several wells, the capacity can reach 50+ MWh , which is commensurate with the objects of Energy Vault [14]. This approach minimizes technical risks and allows for gradual commissioning of facilities. Such a configuration provides high investment attractiveness of the project due to the possibility of phased financing. Therefore, scalability becomes a key factor in optimizing specific capital costs per unit of stored energy. As a result, the use of WellGES will lead to the re-profiling of oil and gas infrastructure and will contribute to the transformation of depleted fields into industrial energy storage hubs.

Since the movable storage element (load) is located underground (Fig. 1), WellGES does not depend on atmospheric conditions (rain, ice, snow). During operation, WellGES does not use any chemical reactions, which makes it environmentally safe and not limited in the number of cycles of use. Just like in Gravitricity/Energy Vault installations are designed for a long service life (30+ years) [14, 15]. The limitations are due to the mechanical components.

The implementation of this installation has a number of potential challenges, including mechanical limitations. The main challenges are the increase in the mass of the cargo, which entails increased technical requirements for the characteristics of the cable, friction in the pulleys and accelerated wear of the cable and drum during prolonged operation. Also, there is a risk of their corrosion in wet wells. The solution to this problem is to use high-strength materials, such as Kevlar or carbon fiber. Another significant challenge is geological factors and safety aspects: the stability of the well walls, hydraulic processes (the influence of gas and water) and seismic risks, which require the development of complex analytical models. The next significant challenge is the long cycle time, friction losses and the peculiarities of the start/stop modes of the generator.

Despite the challenges, such a system can be an effective tool for integrating renewable energy sources, allowing to accumulate excess electricity during generation and return it to the grid in a timely manner for balancing and covering peak loads. The use of standard, common components on the market ensures affordable installation costs, and the ability to change the mass of the storage load and the number of wells in the field gives broad prospects for scaling energy intensity.

7. Conclusions

1. A structural diagram of WellGES, a downhole gravity energy storage system integrated into deep decommissioned oil and gas wells, has been developed. The load moves in the wellbore, while key components requiring maintenance and repair are located on the surface. This design solution significantly increases the reliability and durability of the system. The system accumulates excess electricity by lifting the load to the wellhead and generates energy during its controlled lowering into the wellbore.

2. The energy consumption of a well gravity energy storage system (WellGES) depends on the well depth, load mass, and efficiency (75–90%). For a typical well with a depth of 2000 m and a load of 4000 kg, the energy consumption is ~22 kWh (including losses).

3. A structural scheme with a 4-fold pulley block, a drum for multilayer laying of the rope along the Archimedes spiral with initial and final diameters of 215 and 1250 mm, respectively, an asynchronous electric motor AIR160M6 and a three-stage cylindrical gearbox TsZU-400 is substantiated. Kinematic and force calculation confirms the effectiveness of the system for practical implementation.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship, or other, that could influence the study and its results presented in this article.

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The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Using artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Oleg Vytyaz: Conceptualization, Methodology, Writing – review & editing; **Ruslan Rachkevych:** Methodology, Investigation, Writing – original draft; **Ivan Petryk:** Methodology, Validation, Writing – review & editing; **Eduard Velikanov**: Formal analysis, Writing – original draft, Funding acquisition.

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