Slope Energy Storage Systems (SESS) in deserts

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Abstract

Slope Energy Storage System (SESS) is a form of gravitational energy storage [1] [2] designed to store and release energy by moving heavy rail-mounted masses along inclined tracks. This technology is particularly suited for large-scale renewable energy plants in arid regions where water-based pumped hydro is impractical. The SESS uses Special Railway vehicle (SRV) loaded with heavy-mass materials, moving them uphill using surplus renewable power and recovering electricity during downhill descent via onboard alternators and mechanical systems. This paper describes the working principle, challenges, and components of *a ready-to-deploy & easy to run and maintain SESS*, highlighting its potential for deployment in vast unpopulated areas such as the Middle East where renewable energy production must be matched with efficient and robust energy storage capacity.

Keywords: gravitational energy storage, slope energy storage, easy-to-run-and-maintain

1 Introduction

Gravitational energy storage is a method of storing and releasing energy by moving solid masses vertically or along an inclined plane under the force of gravity. When excess electricity is available (for example, from solar or wind), it powers motors or winches to lift these heavy masses to a higher position, storing gravitational potential energy. Later, when electricity is needed, the masses are lowered, and their descent drives generators through mechanical systems, converting stored energy back into electrical energy. Power is proportional to solid masses speed.

Unlike pumped hydro storage, which raises water to a higher reservoir, SESS raises solid objects, making it particularly useful where water reservoirs are impractical, such as in arid regions or densely built environments.

As an example, regardless of mechanical feasibility and in purely gravitational terms, a load with a 10x2x2 m ferrite block (200 tons) running on a 5% slope with a 10 km track, and converting gravitational potential energy via an alternator (80% efficiency) with overall 90% mechanical efficiency, can deliver around 200 kWh to the grid. Renewable energy can also be used to lift the vehicle, converting electrical energy into stored gravitational energy, that will become available when the loads or the grid need it.

To reduce the costs associated with gravitational energy storage, it is preferable to utilize existing systems such as train wagons instead developing new freight devices. The special rail vehicle will be designed using commercially available widely tested and highly reliable standard components: wheelsets, bearings, brake systems, traction motors/alternators etc.

These systems should already available and proven, making them easy to implement without the need for extensive new types of infrastructure. Additionally, they should be readily equippable with alternators to convert stored gravitational energy into electricity efficiently. Their simplicity and widespread use also mean they are easy to maintain, further lowering overall operational expenses. Using such existing and reliable systems offers a practical and cost-effective approach to economically build and manage gravitational energy storage.

2 Main challenges for SESS

Gravitational energy storage systems face several site-related challenges, and more severe conditions are expected when their installation is planned in desert areas.

- Energy density limitations: relatively low energy per unit mass compared to batteries, requiring large masses or significant elevation. This means that to store significant amounts of energy, large masses or substantial elevation changes are required, which can lead to increased infrastructure costs and space requirements. Consequently, gravitational energy storage is more suitable for grid-scale applications where ample space and elevation are available, rather than for compact energy storage needs.
- Site constraints: the area selected for SESS must have adequate slope and be free from physical barriers that could impede construction of rails. Also weather conditions play a major role in the selection of the installation site, since areas with flood of storm (including sand storms) have to be excluded.
- Environmental limitations: building railway tracks in desert areas presents several environmental limitations. Deserts experience significant temperature fluctuations, with scorching daytime temperatures and much cooler nights: this can cause thermal expansion and contraction in the railway materials, requiring special materials or construction techniques to prevent warping and damage. Wind-blown sand can accumulate on tracks, leading to maintenance challenges and potential derailments. Regular clearing and protective measures, such as barriers, may be necessary. Desert soils can be loose and unstable, which may require soil stabilization techniques or special foundations to secure the tracks.

Mechanical challenges include:

- Mechanical wear and tear: stress on rails, bearings, and couplings. Mechanical wear and tear on railways and wagons is a significant issue affecting their longevity and performance. The components involved and the types of stress they endure can be summarized as follows:
    - Stress on rails: rolling contact fatigue: the continuous passage of wheels over the rails causes surface and sub-surface fatigue cracks, eventually leading to rail fractures. Thermal expansion: changes in temperature can cause the rails to expand and contract, leading to stresses that can cause buckling or misalignment. Wear and abrasion: constant friction between the wheels and rails leads to material being worn away, affecting the rail geometry and requiring regular grinding or replacement. Impact stresses: when trains pass over joints, welds, or imperfections in the track, impact stresses can lead to rail defects such as corrugations or fractures.
    - Stress on bearings: rotational stress: bearings in the wheel assemblies endure constant rotational movement, leading to fatigue over time. Load stress: bearings experience high stresses from the weight of the wagons, especially at high speeds or with heavy loads, potentially leading to overheating or failure. Contamination: dust and debris can infiltrate bearings, leading to increased friction and wear.
    - Stress on couplings: tensile and compressive forces: couplings experience significant longitudinal forces during train movement, especially when accelerating or decelerating, which can cause stretching or compression stress. Impact forces: during shunting and coupling operations, impact forces can damage or wear out the coupling mechanisms. Corrosion: exposure to different weather conditions can lead to rust and corrosion, weakening the coupling components over time.

Managing these stresses requires regular maintenance, including inspections, lubrication, timely replacement of worn parts, and employing materials and designs that can withstand the operational environment. Additionally, advanced monitoring technologies can help predict failures and improve maintenance scheduling.

For this purpose, a diagnostic vehicle will be provided, equipped with all the necessary tools and technologies to detect wear and damage to the tracks, wheelsets, axles, bearings, brake discs, power lines, and the grid feeder. In general, any component or device subject to wear or possible malfunction can be monitored. Based on the information acquired by the diagnostic vehicle and transmitted to the control room; predictive, preventive, or even corrective maintenance interventions will be planned.

Management challenges include:

- Maintenance needs due to frequent cycling. Mechanical component inspection includes regular checks of structural components for fatigue, wear, or corrosion. Inspection of tanks, reservoirs, or flywheel housings for cracks or leaks is necessary. Also, routine lubrication of moving parts like pumps, turbines, bearings, and gears is a major issue.
- Monitoring bearing conditions for signs of wear or overheating.
- Efficiency losses due to rolling and drag resistance: friction losses, friction between moving mechanical parts, such as wheelsets, bearings, and gearboxes cause energy dissipation, that reduces the amount of energy that can be effectively stored and retrieved. Rolling resistance between moving parts such as wheels, pulleys, or the storage medium causes continuous energy dissipation. Higher load and faster operation increase rolling

resistance, further decreasing efficiency. Aerodynamic drag: moving components like turbines and flywheels face air or water resistance. Drag forces convert kinetic energy into heat, lowering the overall efficiency of energy conversion and retrieval. These combined losses typically result in efficiency reductions ranging from 5% to 15%, depending on system design, operational parameters, and maintenance quality. Minimizing these losses involves using high-quality lubricants, streamlined components, precise alignment, and up-to-date maintenance practices to optimize system performance. Furthermore, the vehicle will be equipped with appropriate fairings which will allow for the reduction of losses due to aerodynamic resistance.
- Environmental exposure: corrosion, sand storms, wind loads, track contamination.

Electrical challenges involve:
- Losses in generators. Electrical losses include resistive losses in windings, core losses (hysteresis and eddy currents), and magnetic losses within the generator. Mechanical Losses include friction within bearings and other moving parts convert some energy into heat, reducing net output.
- Losses in converters. Power Electronics: involve losses in inverters and rectifiers used to convert AC to DC or vice versa. Switching Losses include energy lost during the switching of semiconductor devices. Conduction Losses: due to resistance in electronic components during current flow.
- Losses in electronics: monitoring and control electronics, electrical energy for sensors, controllers, and communication systems. Filtering and protection devices: additional minor losses during operation.

Control and safety challenges include:
- Precise braking and speed control in gravitational energy storage systems are essential for maximizing generated energy and maintaining safety, efficiency, and system longevity and include:
  - electromagnetic braking: employs eddy current brakes or magnetic drag to provide smooth, contactless braking, reducing wear and maintenance;
  - mechanical braking utilizing friction brakes or mechanical clamps to rapidly and reliably detain moving components, especially during emergency stops or shutdowns, will be available just for safety reasons since they normally dissipate too much energy;
  - hydraulic braking: uses hydraulic systems for controlled deceleration, especially in large-scale applications;
  - variable-speed operation adjusts the rate of energy transfer by controlling rotating components via adjustable drives or converters (e.g., variable frequency drives for turbines/generators);
  - regenerative braking converts kinetic energy back into electrical energy during deceleration, which can be stored or fed back into the grid;
  - advanced control algorithms: Use real-time sensors and control systems to maintain desired speeds precisely during energy cycling, minimizing oscillations and fluctuations;
  - sensors utilize speed encoders, load cells, and accelerometers for accurate real-time measurement;
  - controllers employ digital control units for precise regulation of braking force and rotational speed.
  - incorporated fail-safe mechanisms and redundancies to ensure reliable operation under all conditions.
- Protection of mechanical components from excessive stress.
- Synchronization with grid frequency and power demands.

Redundancy includes:
- component redundancy: incorporating multiple motor/generator units allows continuous operation even if one component fails;
- control system redundancy: multiple control pathways and backup systems ensure safe operation and fault tolerance;
- communication redundancy: multiple communication channels prevent failures in control signals, enhancing system resilience;
- structural redundancy: designing structural components to withstand unexpected loads or failures without catastrophic consequences.

Rapid grid response can be achieved by:
- fast starting and stopping: ability to quickly ramp up or down energy output helps stabilize grid frequency during disturbances;

- fast power modulation: precise control of energy flow (via variable-speed operation) enables immediate response to grid demands or sudden fluctuations;
- energy buffering: the system's inherent capability to absorb or supply energy rapidly acts as a buffer against grid disturbances;
- advanced control algorithms: implementation of real-time, predictive, or model-based controls enables swift response.

3 The SESS: system description

With reference to Figures 1, 2 and 3 the SESS system harnesses gravitational potential energy as a large-scale energy storage solution by using Special Railways vehicles (SRV) loaded with heavy ferrite material. The SRV operate on dedicated rail tracks built with significant elevation differences, creating an effective medium for storing and releasing energy.

Renewable energy sources such as photovoltaic (PV) solar arrays and wind turbines generate electricity. This power is used to drive traction systems that transport the ferrite-loaded wagons uphill. By raising the SRV to a higher elevation, the system stores energy in the form of gravitational potential energy. The amount of stored energy is determined by the mass of the loaded wagons, the height of the elevation, and gravitational acceleration.

When electrical demand rises or renewable generation drops, the wagons are released to travel downhill under controlled conditions. As they descend, regenerative braking systems convert their kinetic energy back into electrical energy. The power output during this process is proportional to the speed of descent, which is actively managed to meet real-time grid demands and to prevent mechanical stress on the infrastructure.

Between the regenerative braking system of the SRV and the electrical grid, a series of buffer chemical storage units—such as advanced battery banks—are installed. These buffers stabilize fluctuations in power output, ensuring a smooth and reliable supply of electricity to the grid even when wagon speed varies or when short-term interruptions occur.

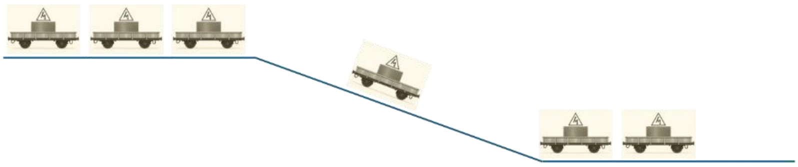

Figure 1: the SESS system (concept)

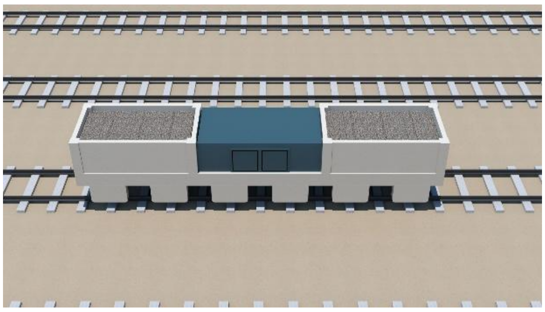

Figure 2: the Special Railway Vehicle (SRV)

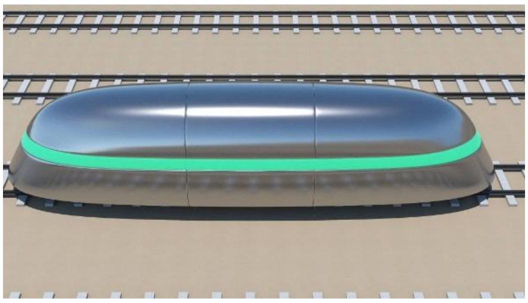

Figure 3: the Special Railway Vehicle (SRV) - conceptual view

The type of rolling stock used in a gravitational energy storage railway system is determined by the combination of weight and slope, while accounting for wheel–rail adhesion. Beyond a certain gradient, conventional adhesion becomes insufficient, and rack-and-pinion systems or cable-hauled solutions may be required. The selection of railway rolling stock for gravitational energy storage applications is in fact governed by the interplay between vehicle mass, track gradient, and wheel–rail adhesion limits. For gradients exceeding the adhesion capacity of conventional systems, alternative traction solutions—such as rack-and-pinion mechanisms or cable-haulage systems—must be adopted to ensure safe and reliable operation.

The system's operational logistics are managed through advanced artificial intelligence algorithms. AI coordinates wagon movements, determines optimal charging and discharging times, predicts renewable energy availability, and schedules SRV deployment based on grid demand forecasts. SRV are strategically parked both at the top of the hill (fully charged position) and at the bottom (ready to be charged), ensuring quick responsiveness to grid requirements.

This combination of gravitational storage, renewable energy input, and AI management creates a flexible, sustainable, and high-capacity energy storage method capable of stabilizing electrical grids with a high penetration of intermittent renewable energy sources.

4 Main components of the system and design constraints

The Smart Energy Storage System (SESS) is conceived as an integrated technological solution built around clearly defined components and precise design constraints that ensure a balance between functionality, safety, and long-term reliability. Its architecture is primarily centered on three main domains: the SRV structure, power electronics, and control & safety systems, each of which contributes to enabling the effective conversion of mechanical energy from train movement into usable electrical energy. Importantly, the SRV designers and manufacturers as well as the subjects entitled to the construction of the complete railway infrastructure -including the traction system and the power supply line- and the providers of the technological subsystems have already been identified, which guarantees not only a mature supply chain but also strong alignment with project requirements from the earliest development stages.

With reference to Figure 4, the SRV is the physical backbone of the system. It will rely on a railway vehicle with a robust steel frame specifically designed to sustain high-mass loads (e.g. ferrite) under demanding operating conditions. A central criterion of the design is adherence to the principle of "maximum possible weights for each axle," which ensures the SRV are optimized for carrying heavy payloads without compromising on safety or durability. To minimize energy losses during operation, the wagons are equipped with high-quality bearings and rail alignment systems that substantially reduce rolling resistance, thereby enhancing the efficiency of the energy capture process. The structure is further designed to host an onboard alternator, with a mechanical interface—whether pantograph, rack, cable, or other defined solutions— that is being finalized. This alternator allows for the direct mechanical-to-electrical energy conversion, and the energy harvested is routed through a grid interface that may include intermediate chemical storage systems. In addition, gear ratios are optimized according to different train velocities, ensuring that energy generation remains effective across varied operational contexts such as steep descents or long-haul transport. Beyond a certain gradient, conventional adhesion becomes insufficient, and rack-and-pinion systems or cable-hauled solutions may be required.

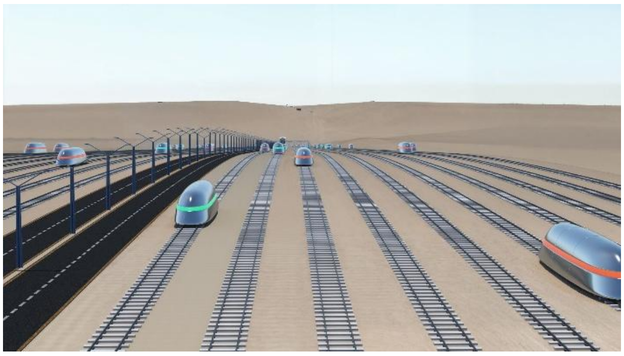

Figure 4: the SESS system - conceptual view

The power electronics domain provides the essential conversion and conditioning functions necessary for grid compatibility. A rectifier transforms the alternator's alternating current (AC) output into direct current (DC), which then passes through advanced AC/DC or DC/AC inverter systems to produce grid-compliant electrical power. This modular approach guarantees flexibility in integrating the system with diverse grid infrastructures. Complementing this is a load control unit that plays a critical role in regulating the generator torque and managing the descent speed of the wagon, ensuring that energy harvesting remains both safe and efficient. By controlling the energy conversion process, these subsystems guarantee stable and predictable power output regardless of external operating conditions.

The control and safety systems layer ensures secure operation and optimizes the system's interaction with both the train and the grid. Electronic braking is carefully coordinated with generator load, providing smooth deceleration and maximizing energy recovery. As a fail-safe measure, robust emergency mechanical brakes are integrated into the design. Automated safety protocols enable the system to shut down immediately in case of overspeed, overvoltage, or mechanical faults, thus safeguarding both the equipment and its operators. On the digital side, the SESS employs an AI-powered management platform designed to interact intelligently with the energy grid. This platform dynamically decides on energy storage versus direct release to the grid, factoring in criteria such as fluctuating energy prices, real-time local demand, and the flexibility needs of the grid. This advanced layer of intelligence transforms the system into not only a storage device but also a grid-balancing tool, capable of supporting modern energy transition goals.

Altogether, the SESS system represents a carefully balanced convergence of mechanical engineering, power electronics, and digital intelligence. By combining durable heavy wagon structures with cutting-edge conversion technologies and AI-driven control mechanisms, the system is positioned to deliver meaningful contributions to energy recovery and grid stability. The fact that wagon manufacturers and technology providers have already been identified underscores the maturity of the initiative and highlights a clear roadmap toward practical deployment. This ensures that from design to execution, the system is supported by capable industrial partners fully aligned with its ambitious objectives.

5. How and where to implement the system

To define how to implement the system, it is necessary to carry out an analysis of the conditions present in the territory considered, not only topographical and geological but also regulatory, social and cultural aspects.
First of all, there must be adequate and long natural slopes on which to define the process, outside of interference with other critical systems or civil structures. Other aspects inherent in the engineering implementation process must then be evaluated. Once the site and performance targets have been chosen, the system should evaluate all possible alternatives related to the use of machines, methods, criteria for measuring demands and service delivery, asset management, labor organization, impact of investments and operating costs.

Possible complementary actions should be evaluated with local consumers which may presumably be present, such as desalination plants, cement, refineries, irrigation systems, wastewater treatment plants, municipal waste treatment systems.

Choice of Manpower. Operational activities to support the operations of the system must also be considered. A highly automated system would require skilled personnel to assist while a low-sophisticated system might require *fewer skills* and perhaps *more arms*. Again, it is a matter of optimizing through a SWOT (strengths, weaknesses, opportunities and threats) and cost analysis for each project.

Availability of Capital and Environmental Opportunities
The exploitation of existing suitable structures can be advantageous both in terms of costs and in terms of construction time. In any case, new infrastructures will be needed. In the choice of location, in addition to the natural slope, it is necessary to check for the presence of roads, railways, aqueducts, oil pipelines, etc., i.e. areas that may be suitable for SESS, without incurring expropriation and preparatory or auxiliary works.

Critical success factors are the simplicity of the mechanical systems, the ease of management and maintenance and the possibility of using workers with average skills, creating job opportunities on site and promoting social acceptance of the technology by local communities.

[1] Wang, R.; Zhang, L.; Shi, C.; Zhao, C. "A Review of Gravity Energy Storage". Energies. April 2025.
[2] Wu, C.; Lu, S.; Xue, F.; Jiang, L. "Earth Potential as the Energy Storage in Rail Transit System - On a Vertical Alignment Optimization Problem". In Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4-7 November 2018; pp. 2729–2734.