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The power of sand: Can solid gravity close the energy storage gap?

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ABSTRACT

Transition to low-carbon energy systems primarily based on variable renewable energy, such as wind and solar, requires flexibility options, including energy storage. While batteries have dominated the market for short-term electricity storage, existing alternatives for long-duration energy storage are either site-specific, such as pumped hydropower storage (PHS), or lack the required supply infrastructure, such as green hydrogen and other synthetic fuels. We investigate the world's potential and project-specific cost of four emerging gravity energy storage technologies that are carbon-free and can be *integrated* into existing infrastructure: mountain gravity energy storage, electric truck gravity energy storage, underground energy storage, and lift energy storage technology. These electricity storage technologies can reach a levelized cost of (seasonal) energy storage as low as 94 USD MWh^{-1} and can store up to nearly 231 TWh of electricity globally (cf., the world's PHS total installed capacity is estimated to be 8.5–9 TWh today). Integrated gravity can play a role as long-duration energy storage in decarbonizing the energy sector and is a complementary solution to short-duration energy storage such as battery energy storage systems (BESS).

1. Introduction

Net-zero energy transition pathways underscore a rapid deployment of variable renewable energy (VRE) sources, namely wind and solar energy. To facilitate a high share of VRE, net-zero scenarios suggest the need for large-scale deployment of electricity storage technologies [1]. The International Energy Agency (IEA) estimates the need for the rapid expansion of short-duration, grid-scale energy storage capacity, from 150 GW in 2024 to nearly 1000 GW by 2030 globally [2]. In addition, the world's need for long-duration energy storage (LDES) is projected to amount to 2500 GW (140 TWh) by 2040, 15 times larger than the current installed capacity of pumped hydropower storage (PHS), to stay in track with the Paris Agreement climate goals [3].

The two most common electrical energy storage (EES) systems today are batteries and PHS [4]. Stationary batteries offer a low-cost solution for intraday energy storage and provision of ancillary services to the grid [5]. With over 69 GW/169 GWh capacity installed in 2024 alone, batteries have dominated the market for short-term energy storage, particularly due to the rapid cost decline, accelerated project scale-up and implementation, and benefiting from synergetic development with electric mobility [6]. Using batteries to store energy for more than a few days or weeks may not be economically viable [7]. Furthermore, the significant reliance on specific raw materials, a highly concentrated global supply chain of battery components, and the widespread use of batteries in mobility applications raise concerns about the large-scale application of batteries in the electricity sector [8].

PHS plants are currently the only economically viable solution to store large amounts of energy in weekly, monthly, seasonal, and pluri-annual cycles [9]. However, PHS's potential is severely limited by topographic, geological, and hydrological conditions, which might not allow the technology to scale up as rapidly and sufficiently as needed for energy storage required in net-zero carbon emission scenarios. Hydrogen and other synthetic fuels have low AC-to-AC efficiency and high capital costs [10] and are arguably suitable for addressing the common energy storage needs of a growing energy system [46], even though they can be prime solutions for decarbonizing hard-to-abate

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sectors such as specific industry applications and aviation [11]. Thus, other alternatives for LDES are needed to enable the energy sector decarbonization [12].

Gravity energy storage (GES) is an alternative for storing electricity in the form of potential energy by lifting solid objects or sand/gravel to high altitudes and generating electricity by releasing the lifted object and converting stored gravitational energy to electric energy. This mode of energy storage has received much attention lately[2], with research and innovation on different designs [14]. We categorize GES into two main groups: modular versus integrated GES. In a *modular* GES, the height difference between the upper and lower storage sites must be created by constructing a dedicated infrastructure, e.g., a tall enough storage building or a crane tower must be built for storing concrete blocks. This limits the application to short storage cycles, such as hourly, daily, or weekly energy storage, as expanding the storage size in such built infrastructure is typically very expensive. With the reduction in the costs of batteries, this GES type might only become competitive for weekly energy storage. On the contrary, the *integrated* GES leverages an existing height difference in a natural site or man-made infrastructure, such as mountains, mines, or high-rise buildings, to store energy. This allows for longer storage cycles, such as monthly, seasonal, and multi-year storage, as the cost of storage will be significantly lower than a modular project, and it would mainly consist of the storage media, i.e., sand[3]. These two GES types are described in more detail in Table A1 in Appendix.

Several papers have reviewed the techno-economic characteristics of GES, comparing these novel technologies with other storage solutions [13,14]. The economic viability of GES technologies in single projects has been evaluated for specific sites or storage services [15,16]. Yet, there is a research gap in assessing the potential of integrated GES in different world regions linked with the levelized cost of energy storage (LCOS) for various storage durations, to which this paper contributes. While the literature has focused on the potential assessment of individual GES technologies, this study explores the combined potential of integrated GES technologies and provides a high-resolution, open dataset of potential GES sites globally. Our analysis and the resulting dataset can contribute to a better understanding of emerging LDES options that can be part of the transition to a net-zero energy system. The findings of this paper, including the GES cost-potential dataset, can be useful information for technology developers, policymakers, and energy modelers.

The rest of the paper is structured as follows. Section 2 describes GES, with a focus on those technologies evaluated in this paper. The methods and data are presented in Section 3, followed by the results in Section 4. Discussion and conclusions are summarized in Section 5.

2. Emerging gravity energy storage technologies

The first large-scale GES plant has been built in China with 100 MWh storage capacity [17]. The technology consists of constructing a building that stores concrete blocks at different altitudes. The concept is similar to lift energy storage technology [18], however, the latter uses existing buildings and lifts to provide energy storage services. Advanced Rail Energy Storage uses trains connected to cables to transport concrete blocks from a lower to an upper storage location [19–22]. This technology resembles electric truck gravity energy storage [30], however, the second uses existing roads, and the trucks can transport cargo when the demand for seasonal energy storage or generation is low. Others propose storing potential energy in existing mining shafts by moving a giant mass up and down [15,24,25].

This paper investigates the cost and global potential of four emerging GES technologies. These include mountain gravity energy storage [28] (MGES), underground gravity energy storage [29] (UGES), electric truck gravity energy storage [30] (ETGES), and lift energy storage technology [18] (LEST) (Fig. 1). These technologies are based on storing energy by transporting bulk sand or mine tailing from a lower to an upper storage site. The higher the altitude difference between the upper and lower reservoirs, the more gravitational energy can be stored per kilogram of material, and the lower the energy storage unit costs. For further technical details and analysis elaborating on the working principles of their GES technologies and their respective application scenarios, please refer to the references above.

MGES consists of transporting sand with cranes, storage vessels like buckets, and cables [28]. It is applicable to mountainous areas, where the topography results in slope gradients greater than 100 % (i.e., the ratio of vertical distance to horizontal distance). A real-world example of a similar use case is the UK's last aerial ropeway, which moves shale to a brickmaking facility a mile and a half away with no power input [31].

ETGES uses dump trucks to store energy and carry the sand up a mountain [30]. Electricity is generated by applying the regenerative braking system of the electricity truck when moving down the sand. The slope gradient in ETGES should vary from 10 to 20 % to increase the viability of storing energy. As there is a limited number of existing steep roads, purposely made roads or road sections might have to be built for such applications. A similar real-world application is the use of the world's first electric dump trucks in Switzerland that can store electricity while descending tons of load [32]. When possible, ETGES is combined with Electric Truck Hydropower (ETH) to increase the viability and efficiency of the system. ETH carries water when the dump truck drives down the mountain without sand. ETGES might also be combined with MGES and/or UGES to enhance the plant's storage capacity.

UGES uses empty decommissioned underground mines [29]. Electricity is generated while filling the empty underground mine using cables and a series of vessels and motors/generators. Energy is stored by extracting the sand from the mine and depositing it around the mine shaft with dump trucks, conveyor booms, excavators, bucket wheel excavators, and soil compactors. The estimated potential for UGES in this paper is limited to coal mines [33], due to the lack of a detailed database on other underground mine deposits.

LEST stores energy in high-rise buildings by transporting containers with sand from lower storage sites (such as empty or sub-utilized apartments, corridors, garages, or outside buildings) to the lift via autonomous trailers. The lift raises the containers and trailer to the upper storage site (such as empty or sub-utilized apartments, corridors, or on the building's roof) [18]. The lift can operate together with the transportation of people or can operate only when the lift is not being utilized, e.g., during off-peak periods or at night. This would depend on the interest of the building manager. The main challenge of this technology is the availability of space in the building to accommodate a storage container filled with sand and additional maintenance and safety considerations for the use of lifts in a more demanding service.

3. Methods and data

The methodology applied in this paper is divided into two main parts. The first part is to estimate the LCOS, and the second part is to estimate the global potential for GES technologies investigated in the paper. The equation used to calculate the LCOS is presented below. Where: P_{cap} is the power capacity (in MW), P_{capex} is the power CAPEX (in USD/MW), P_{opex} is the power OPEX (in USD/MW/year), E_{cap} is the energy storage capacity (in MWh), E_{capex} is the energy storage CAPEX (in USD/MWh), d_P power discount factor (years), d_E energy storage discount factor (years), CF capacity factor (in %), h is the 'default height difference' between the upper and lower reservoirs (in m) (See Table A2

[2] Gravity energy storage was named one of TIME Magazine's Best Inventions of 2024 in the "Green Energy" category. https://time.com/7094811/energy-vault-evx/

[3] While sand is used as a reference to a bulky, solid storage medium in this paper, other materials with similar characteristics may be used as well, e.g., gravel.

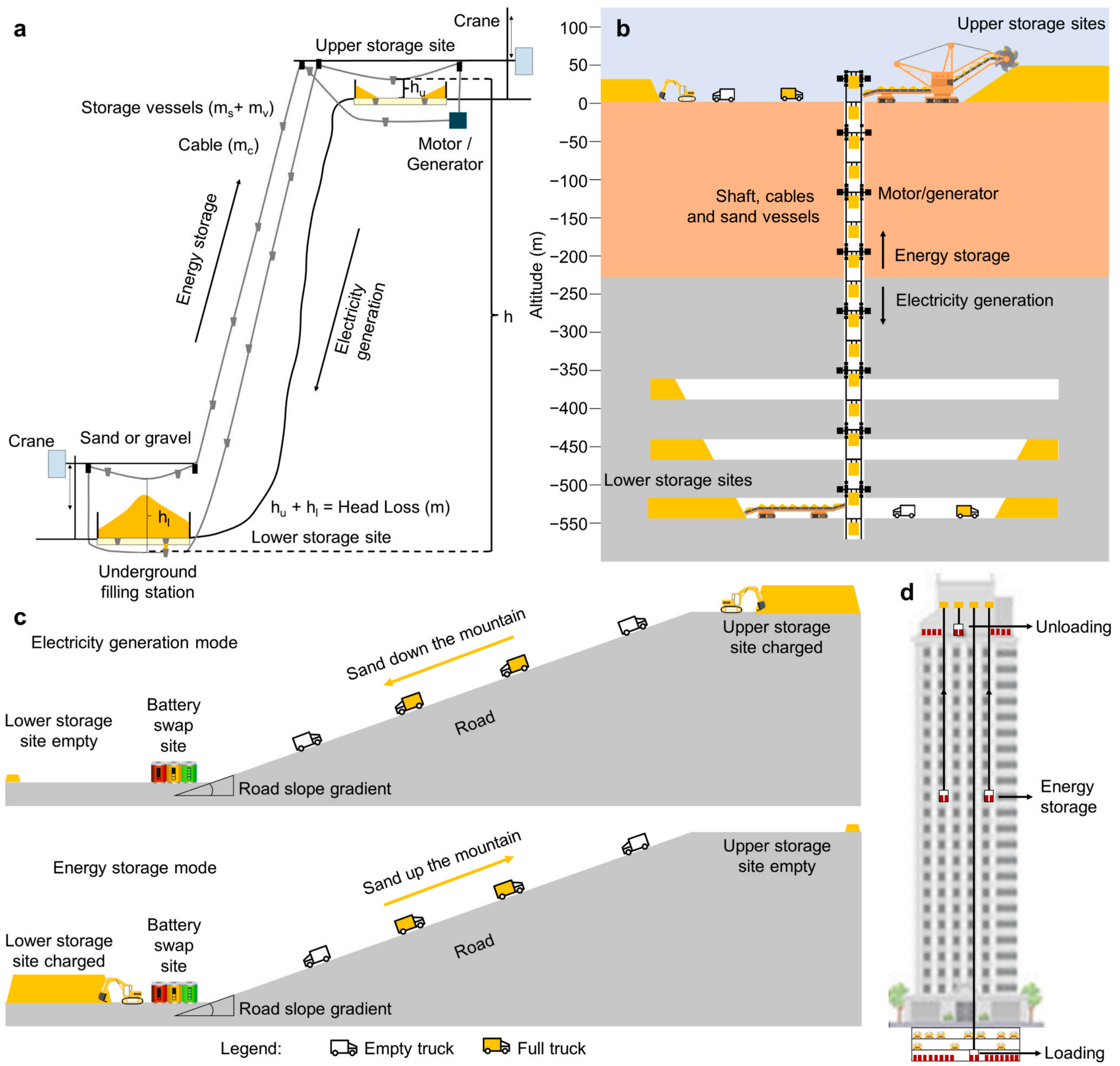

Fig. 1. Emerging gravity energy storage technologies and their charge-discharge cycle, (a) mountain gravity energy storage (MGES) [28], (b) underground gravity energy storage (UGES) [29], (c) electric truck gravity energy storage (ETGES) [30], and (d) lift energy storage technology (LEST) [18]. (Images are adopted from the cited article for each technology with minor changes).

in Appendix), H is the actual height difference between the upper and lower reservoirs (in m).

$$LCOS = \frac{P_{cap} \times P_{capex}\left(\frac{1}{d_P} + P_{opex}\right)}{P_{cap} \times CF \times 8760} + \frac{\frac{\left(\frac{E_{cap} \times E_{capex}}{d_E}\right)}{E_{cap} \times CF \times 8760} \times h}{H} \quad (1)$$

The global potential for GES models was created in Python, and the source code will be made available on request. A description of the methodologies for each technology is as follows. To analyze the worldwide potential for MGES [28], we lower the resolution of the global topographic data [34] to 5-min resolution, which is equivalent to 9 km at the equator. We used a 5-min spatial resolution because it is the resolution of the road infrastructure data from [35]. The actual height difference (H) for each location is estimated by subtracting the altitude of the pixel under analysis by the pixels surrounding it vertically and horizontally. The other parameters in Eq. 1 do not vary. In the case of UGES, the worldwide potential for UGES [29] was estimated using a database with somewhat more than three thousand records. The database solely contains records on coal mines. This sample is, unfortunately, smaller than the figure given in the introduction.

A comprehensive, worldwide, and open database, on the other hand, is now lacking. The database contains the depth of the mines, however, it does not have information on the mines' volume. We assume that the mines can store 40 million tons of sand. Using databases [36,37], the worldwide potential of LEST was assessed by calculating the number of existing high-rise structures and their heights. Only structures taller than 50 m were included in our research, as lesser buildings have higher storage costs. The database includes 22,585 buildings from across the world. The average height of the structures under consideration is 120 m. Conservatively, we assume that each building can bear the bulk of 5000 containers weighing 1 ton each (both in terms of space and ceiling bearing capacity). Assuming a building with 50 × 50 × 120 m, 30 floors, and a load bearing capacity of 3 kN/m^2 [38] per floor can support 22,936 tons, 5000 tons is equivalent to 21.8 % of the designed load bearing capacity of the building. The worldwide topography [34], road networks [35], and hydrological (run-off) [39] data were used to evaluate the global potential for ETGES. The topography data was utilized to calculate the height difference between two points and the road slope. By using a logarithm with a base of 10, the road infrastructure data is turned into a road index. From 1981 to the present, the run-off data set comprises of monthly average land run-off data. Eq. 2 describes the equation used to estimate the ETGES global potential.

$$P = \sum_{i=1}^{n} G_i\left(S_i\left(\frac{\Delta H_i}{D_i}\right), R_i, W_i\right) \text{ if } C\left(S\left(\frac{\Delta H_i}{D_i}\right)\right) < 200 \quad (2)$$

Where: P is the ETGES generating potential for the point under analysis (PUA) (in GWh), i denotes one combination of the PUA and a point around it (PSI), and n denotes the number of PSI surrounding the PUA, which is equal to eight. G is a function of S, R, and H that represents the ETGES generating potential of each road stretch in GWh per year. S is the applicable road slope, while H denotes the minimal height difference between PUA and PSI. The horizontal distance between PUA and PSI is denoted by D. R denotes the road infrastructure that connects PUA and PSI. W is the PSI's annual average surface run-off, which restricts the hydropower potential to the available water. The amount of water considered to assess hydropower potential is 10 % of the river surface flow. The model has many assumptions, which are described in [30]. For more details on the methodology, please refer to the model script.

4. Results and analysis

4.1. The levelized cost of gravity energy storage

The cost for GES varies mainly with the storage duration, the difference in altitude between the upper and lower storage sites, the capacity factor utilization of the installed capacity, the technology, and the cost of sand. The assumptions for these LCOS estimates are described in Table A2 in Appendix, and Supplementary Fig. 1 presents the CAPEX of the technologies. We separated the lifetime of the components of the system for power (cranes, cables, vessels, 15 years) and energy storage (sand, 100 years) costs. Also, the O&M cost for power equipment is high; however, for sand, it is zero. The sand can be sold if, for example, hydrogen becomes a substantially cheaper alternative for energy storage in the future. The capacity factor of the power equipment varies substantially with the storage duration, with daily and weekly storage cycle capacity factors varying from 10 to 20 % and seasonal reaching 35 %. Note that the maximum capacity factor of MGES and UGES is 50 %, as half of the time the plant is generating electricity and the other half storing energy, and for ETGES and LEST is 25 %, as the truck and lift must go up and down twice to generate electricity.

Fig. 2 presents the LCOS estimates for the technologies analyzed in this paper, with varying sand costs. It shows that the cost of daily, weekly, and monthly storage with MGES, ETGES, and UGES is generally higher than seasonal and 3-year storage cycles because of their lower capacity factor. Their cost also does not vary substantially with the difference in altitude higher than 1 km between the upper and lower storage sites, in the seasonal and 3-year cycles. This is because the amount of sand required is small and comprises a small share of the LCOS in those project sizes. The sensitivity of the LCOS of these three technologies to the sand cost is insignificant in daily and weekly storage cycles.

However, these cost values vary substantially with seasonal and 3-year storage cycles as the cost of energy storage becomes more relevant. ETGES LCOS is showing a lower value than the ones in Fig. 2b when compared to global estimates. This is because Fig. 2b assumes a road grade slope of 15 %, while the maximum grade slope assumed in the global potential is 12 %. A road grade slope of 15 % or higher can be achieved if a purposely made road is built for an ETGES plant. This is possible because electric trucks have an engine power rating substantially higher than fossil fuel trucks. For LEST, the cost for seasonal and 3-year storage cycles does not appear in the graph because the costs for the containers required to hold the sand substantially increase the energy storage costs, making LEST more appropriate for daily and weekly energy storage services. Also, LEST LCOS shows the highest sensitivity to the sand cost, e.g., an increase from 1 to 4 USD/ton of sand would increase the LCOS of a weekly storage in a 200 m tall building by 100 USD/MWh.

The assessment of the LCOS for the four examined emerging GES technologies is presented in Fig. 3. The results show that the LCOS for seasonal energy storage with MGES can reach as low as 137 USD/MWh, ETGES 148 USD/MWh, UGES 94 USD/MWh, and for weekly energy storage, LEST 54 USD/MWh. The proposed plants for MGES, ETGES, and UGES assume that the installed capacity of the plant is enough to fill and empty its entire storage capacity in one year and assume a total utilization of the power capacity of 70 %. The dependency of the CAPEX on the height difference is provided in Supplementary Fig. 1, and the project-specific LCOS of the GES technologies globally and in different world regions is provided in Supplementary Figs. 2 and 3, respectively.

4.2. The global potential of gravity energy storage

Fig. 4 presents the global potential for the four GES technologies investigated in this paper. For MGES and ETGES, the energy storage potential is many times larger than that proposed in this paper, considering the substantial availability of high-altitude difference sites to store sand globally. For practical reasons, we restrict the potential for MGES, assuming one project with 40 million tons of sand, the best location/altitude difference per 2-degree resolution, and power capacity varying with the altitude difference (30 MW for a 1000 m height difference). For ETGES, we assume one project with 220 million tons of sand per 2-degree pixel, where there is road infrastructure and water availability for electric truck hydropower on the way down during storage mode (usually summer), 100 MW power capacity for a 1000 m height difference. For UGES, we consider all the available underground coal mines as described in [30], 40 million tons of sand, and 30 MW power capacity for a 1000 m height difference. For LEST, we consider all buildings in the globe higher than 50 m as described in [18], 50 thousand tons of sand, and 13 kW of power capacity per building.

The overall potential for LEST is the smallest and equal to 0.16 TWh. This is because there is only a small potential for storing sand in buildings due to the limited space available and the ceiling-bearing capacity limitation of buildings. On the other hand, UGES, MGES, and ETGES can store much more sand, and we estimate the storage potential for UGES at 75 TWh, MGES at 115 TWh, and ETGES at 41 TWh. Table 1 compares the techno-economic characteristics and the global potential of the four emerging GES technologies examined in this paper.

5. Discussion and conclusions

The MGES, ETGES, and UGES technologies have a high power-capacity cost (USD/MW) but low storage cost (USD/MWh), which makes them particularly interesting for long-term storage cycles, such as seasonal and pluriannual. They can still operate on weekly and monthly storage cycles if the system is already operational. However, these systems would not compete with batteries to store energy in daily cycles due to the lower efficiencies and higher O&M costs, but in emergency scenarios. Due to the high cost of power capacity, these storage technologies should not surpass ~100 MW per project.

On the other hand, the cost of power in LEST is low, as the existing lift infrastructure of the building with a regenerative braking system is used, and the cost for storage is higher due to the need for containers to store the sand and cover the costs of storing the containers in the

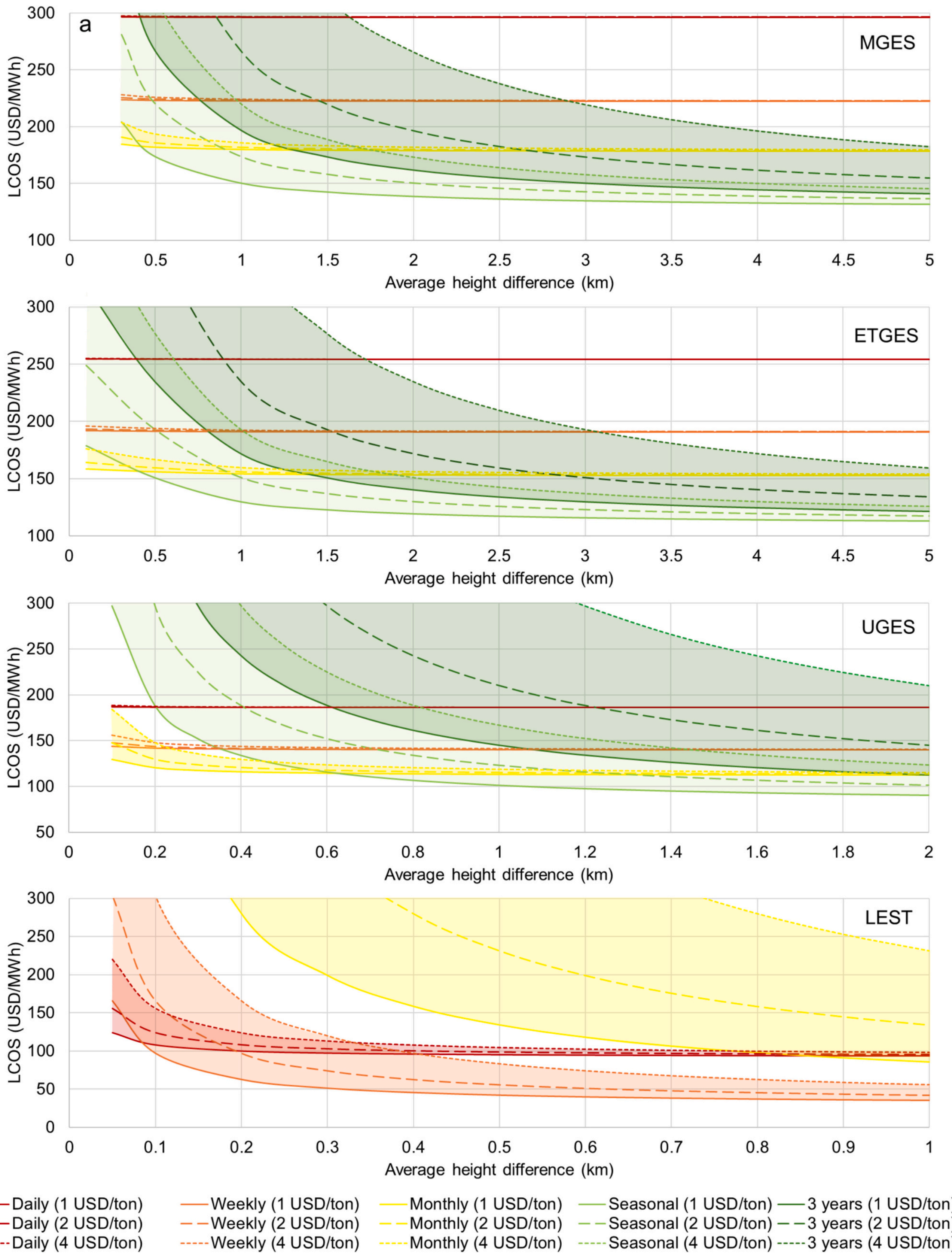

Fig. 2. Levelized cost of energy storage for daily, weekly, monthly, seasonal, and 3-year storage cycles variation with the difference in altitude between the upper and lower storage sites, and sand costs for: a) MGES, b) UGES, c) ETGES, and d) LEST.

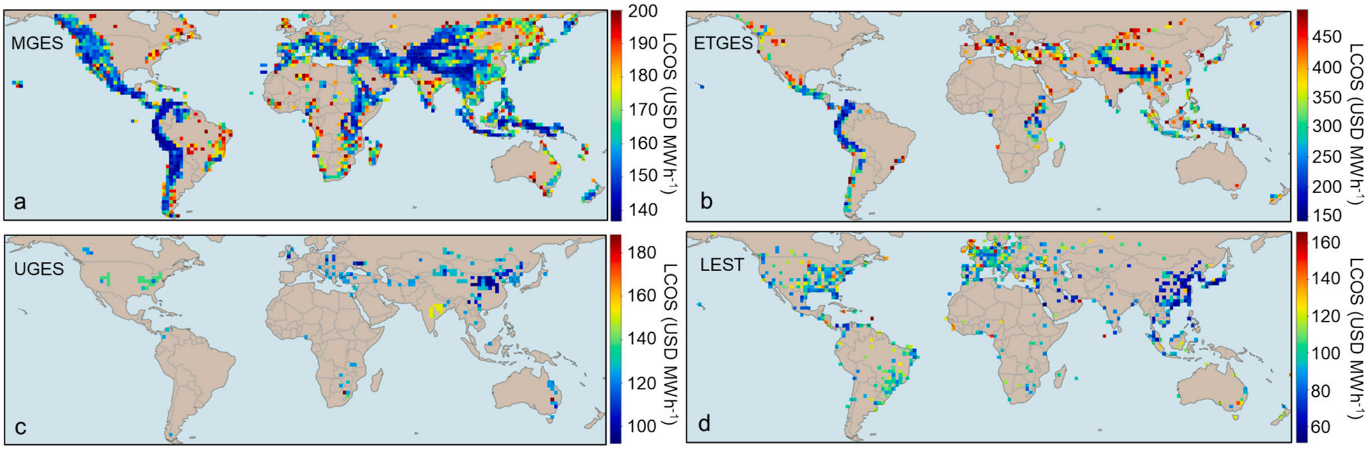

Fig. 3. The levelized cost of energy storage (LCOS) of gravity energy storage technologies for individual projects worldwide. a) MGES, b) ETGES, c) UGES, and d) LEST.

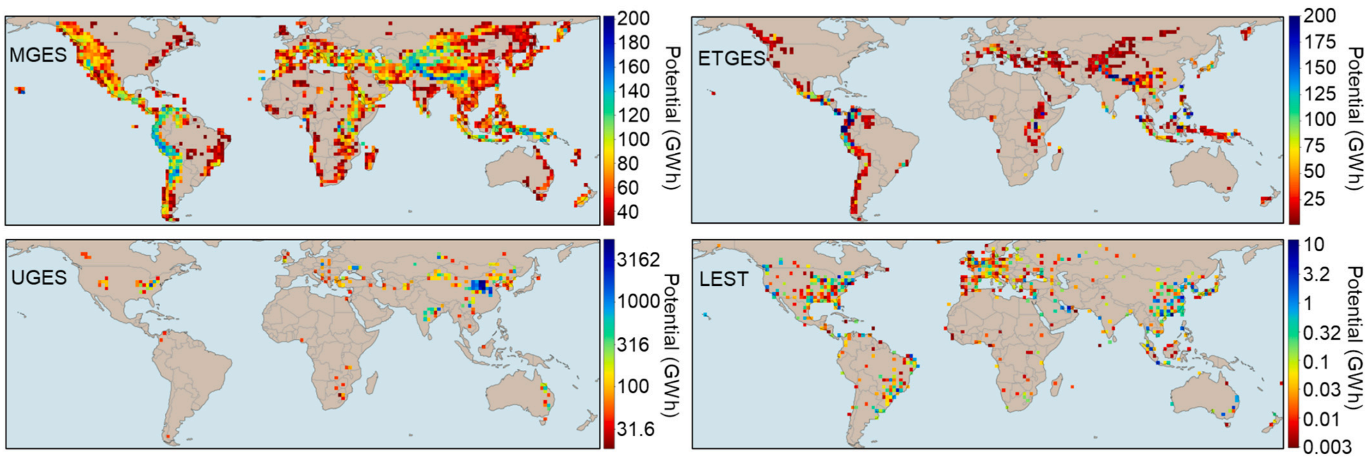

Fig. 4. Global potential for gravity energy storage technologies in terms of storage size (GWh) for a) MGES [28], b) ETGES [30], c) UGES [29], and d) LEST [18]. The methodology for estimating these potentials is adopted from the respective reference for each technology and modified by the authors to create these figures.

Table 1
Comparison between different gravity energy storage and some commercial energy storage technologies.

Name	Installed capacity cost (USD/kW)	Energy storage cost (USD/kWh)	Installed capacity per project (MW)	Storage cycles	Global potential (TWh)	Reference
Mountain Gravity Energy Storage (MGES)	1000–2000	1–100	1–20	Seasonal, pluriannual4	115	[28]
Electric Truck Gravity Energy Storage (ETGES)	1200	2–100	20–100	Monthly, seasonal, pluriannual	41	[30]
Underground Gravity Energy Storage (UGES)	1000–2000	2–15	1–50	Seasonal, pluriannual	75	[29]
Lift Energy Storage Technology (LEST)	500–1000	20–120	0.02–1 (per building)	Ancillary, daily, weekly, monthly	0.16	[18]
Seasonal pumped hydropower storage (SPHS)	600–1000	2–50	10–1000	Ancillary, hourly, daily, weekly, monthly, seasonal, pluriannual	17,300	[40,41]
Li-ion batteries	300–500	150–200	0.01–500	Ancillary, hourly, daily	No site-limited but material needs	[42]
Compressed air energy storage (CAES)	750–1000	1–100	10–500	Ancillary, hourly, daily	Not available	[41,43]
Hydrogen	300–1000	0.02–100	0.01–1000	Ancillary, hourly, daily, weekly, monthly, seasonal, pluriannual	Not available	[44]

building. The higher storage cost limits the storage cycle to longer periods, like monthly. LEST can be used for daily storage due to higher efficiency, lower O&M costs, and because it is a decentralized technology that stores and generates electricity close to the demand side. The LEST installed capacity is limited to the existing high-rise lifts and varies significantly from building to building.

The estimated global GES potential in this paper is 231 TWh. To reach a total decarbonization of the energy sector, hourly, daily, weekly,

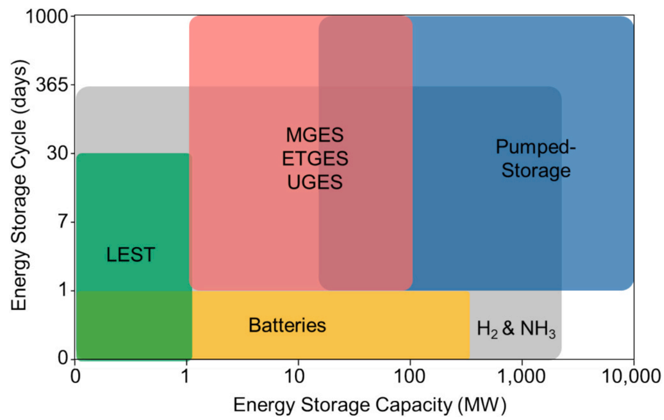

Fig. 5. Gravity energy storage cycle and installed capacity compared with other storage technologies.

monthly, seasonal, and pluriannual energy storage technologies will be required. Where, for example, batteries can provide hourly and daily storage, CAES and LEST can provide weekly and monthly storage, and hydrogen, MGES, UGES, ETGES, and SPHS can provide monthly, seasonal, and pluriannual storage. Fig. 5 illustrates the position of the examined GES technologies compared to other storage solutions along two axes of duration of storage and storage capacity.

Seasonal pumped hydro storage (SPHS) might be a cheaper solution compared to the proposed GES technologies [45], but it requires a large dam and large volumes of water, which can result in significant evaporation, besides environmental damage. Water evaporation is an issue in SPHS, particularly in regions where water is scarce. On the other hand, GES solutions use the power of sand, which does not evaporate or dissipate and can store energy for years.

Even though most proposed GES technologies are designed for hourly or daily energy storage cycles. We argue this is not a well-justified solution as GES has a high power capacity-related cost (USD/kW) but a low energy storage-related cost (USD/kWh). Thus, GES technologies are more likely to be compatible in weekly, monthly, seasonal, and pluriannual storage cycles rather than short-term services, which have better candidates such as batteries. In other words, a GES plant should have a high energy-to-power (EtP) ratio, i.e., relatively small installed power capacity (MW) but a large storage size (GWh) to be cost-competitive.

GES can play an important role in long-term energy storage because storing sand at different existing altitudes is cheap, but moving the sand is expensive. GES will be more feasible when the sand is sitting and storing energy for a long period.

CRediT authorship contribution statement

Julian David Hunt: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Behnam Zakeri:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jakub Jurasz:** Writing – original draft, Formal analysis, Conceptualization. **Yoshihide Wada:** Writing – original draft, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Volker Krey:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Keywan Riahi:** Writing – original draft, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Conceptualization. All authors have been involved in reviewing the manuscript critically.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Jakub Jurasz, serving as an Associate/Managing Editor of the Journal of Energy Storage, was not involved in the editorial or review process of this paper at any of its stages.

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Appendix A

Table A1
Comparison between integrated and modular gravity energy storage (GES) types.

	Gravity energy storage types	
	Integrated	Modular
Technologies	Mountain gravity energy storage (MGES) [28]; Advanced Rail Energy Storage (ARES) [21]; Underground gravity energy storage (UGES) [29]; Electric truck gravity energy storage (ETGES) [30]; Lift gravity energy storage (LGES) [18]; Shaft gravity energy storage (SGES)[24];	Buildings gravity energy storage (BGES)[47]; Piston gravity energy storage (PGES) [15,48];
Storage duration	Hours, daily, weekly, monthly, seasonal, yearly storage cycles	Hourly, daily, and weekly storage cycles
Example companies	Green Gravity [49], Economical Energy [50], Gravitricity [24], Advanced Rail Energy Storage [21]	Energy Vault [51], Gravity Storage [25], Gravity Power [25]
Advantages	- Energy storage costs are low (USD/kWh), mainly for sand or other materials being stored at different heights (for Gravitricity, the energy cost is high because the weight is always suspended with cables). - MGES, UGES, and ETGES can provide seasonal energy storage (ARES cannot	- Location flexibility: It can be built in practically any location. - Can provide weekly energy storage services. - Modularity: Flexible design and sizing depending on the application.

(*continued on next page*)

Table A1 (*continued*)

	Gravity energy storage types	
	Integrated	Modular
Limitations	provide seasonal storage because concrete is substantially more expensive than sand). - The cost of the power conversion system is high (USD/kW) (related to moving the sand from the upper to the lower storage site and vice versa). - For LEST, the additional safety considerations and O&M costs may hinder the application in many buildings. - For UGES and SGES, some underground mines may get flooded with water, which would limit the application. - For MGES, piling a large amount of sand may not be possible due to visual or environmental impact.	- The power conversion system cost is high (USD/kW) (to move the storage blocks or sand from the upper to the lower storage site and vice versa). - Energy storage costs are high (USD/kWh), which is related to the built infrastructure required to hold the heavy mass of the storage media and the material that stores gravity energy.

Table A2
Levelized cost of energy storage estimates for MGES [28], ETGES [30], UGES [29], LEST [18].

Item	MGES	ETGES	UGES	LEST
Installed capacity cost (million USD)	45	150	30	0.015[1]
Storage capacity cost (million USD)	40	220	40	0.055[2]
Average altitude difference (m)	1000	1000	1000	100
Generation efficiency (%)[1]	80	88	85	80
Installed capacity (MW)	30	100	30	13
Energy storage (GWh)	87.2	300	92.65	0.0011
Installed capacity CAPEX (USD/kW)	1.500	1500	1000	1155.96
Energy storage capacity CAPEX (USD/kWh)	0.46	0.73	0.43	50.46
Daily energy storage CAPEX (USD/kWh)	186.86	181.33	117.39	146.79
Weekly energy storage CAPEX (USD/kWh)	27.09	26.53	17.14	64.22
Monthly energy storage CAPEX (USD/kWh)	6.65	6.73	4.32	53.66
Seasonal energy storage CAPEX (USD/kWh)	0.97	1.23	0.76	50.73
3-years energy storage CAPEX (USD/kWh)	0.63	0.90	0.54	50.55
Installed capacity lifetime	15.00	15.00	15.00	15.00
Energy storage capacity lifetime	100.00	100.00	100.00	30.00
Interest rate	0.05	0.05	0.05	0.05
Installed capacity discount factor	10.38	10.38	10.38	10.38
Energy storage capacity discount factor	19.85	19.85	19.85	15.37
Installed capacity O&M costs	15	20	15	10[4]
Daily capacity factor (%)	15	7.5	15	5[5]
Weekly capacity factor (%)	20	10	20	10
Monthly capacity factor (%)	25	12.5	25	12.5
Seasonal capacity factor (%)	35	17.5	35	17.5
3 years capacity factor (%)	35	17.5	35	17.5
LCOS for daily storage (USD/MWh)	293.6	342.2	184.2	112.6
LCOS for weekly storage (USD/MWh)	220.6	257.3	138.6	70.5[6]
LCOS for monthly storage (USD/MWh)	179.9	210.5	113.5	315.4
LCOS for yearly storage (USD/MWh)	150.2	185.1	101.5	3312.3
LCOS for 3 years storage (USD/MWh)	196.5	259.0	145.0	9877.2

[1] Ten autonomous trailers. One autonomous trailer transports one container in 10 min. In one week, it can transport 500 containers to generate electricity. No cost for the building and the lift with regenerative braking, as they already exist.
[2] 5000 containers to store sand, and 5000 tons of sand. No cost for storing the containers.
[3] This consists of only generation efficiency, as the plant generates electricity from a 100 % charged state. In these equations, the storage efficiency is not relevant because we assume the electricity used during the storage process is free.
[4] We assume a medium O&M of 10 % of the investment costs due to the simplicity of the system.
[5] The capacity factor varies mostly with the availability of the lifts to store or generate electricity, not only with the demand for energy storage.
[6] The LEST LCOS for daily and weekly storage is low. However, it is not good for short-term storage because the storage and generation will depend on the availability of the lift. For this reason, it works for weekly storage and not so much for daily storage. LEST is not good for long-term energy storage because the height difference is small and does not justify the cost of the containers and the sand.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2025.116839.

Data availability

Data will be available on request. Interactive maps have been created to better present the potential of each technology in the link: https://www.google.com/maps/d/edit?mid=191ZjmVYCa-6qiQBi0wMNMIA9o6oV_Ek&usp=sharing.

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