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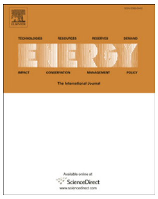

Lift Energy Storage Technology: A solution for decentralized urban energy storage

Julian David Hunt [a, b, *], Andreas Nascimento [b], Behnam Zakeri [a], Jakub Jurasz [c],
Paweł B. Dąbek [d], Paulo Sergio Franco Barbosa [e], Roberto Brandão [f],
Nivalde José de Castro [f], Walter Leal Filho [g], Keywan Riahi [a]

[a] *International Institute for Applied Systems Analysis (IIASA), Austria*
[b] *Federal University of Espírito Santo, Brazil*
[c] *Wrocław University of Science and Technology, Poland*
[d] *Wrocław University of Environmental and Life Sciences, Poland*
[e] *Federal University of Alfenas, Brazil*
[f] *Federal University of Rio de Janeiro, Brazil*
[g] *Hamburg University of Applied Sciences, Germany*

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ABSTRACT

The world is undergoing a rapid energy transformation dominated by growing capacities of renewable energy sources, such as wind and solar power. The intrinsic variable nature of such renewable energy sources calls for affordable energy storage solutions. This paper proposes using lifts and empty apartments in tall buildings to store energy. Lift Energy Storage Technology (LEST) is a gravitational-based storage solution. Energy is stored by lifting wet sand containers or other high-density materials, transported remotely in and out of the lift with autonomous trailer devices. The system requires empty spaces on the top and bottom of the building. An existing lift can be used to transport the containers from the lower apartments to the upper apartments to store energy and from the upper apartments to the lower apartments to generate electricity. The installed storage capacity cost is estimated at 21 to 128 USD/kWh, depending on the height of the building. LEST is particularly interesting for providing decentralized ancillary and energy storage services with daily to weekly energy storage cycles. The global potential for the technology is focused on large cities with high-rise buildings and is estimated to be around 30 to 300 GWh.

1. Introduction

Buildings consume around 40% of electricity worldwide [1]. There are several solutions to increase the efficiency of energy services in buildings. However, there is a limited number of solutions for electricity generation in buildings. The existing ones can include solar power generation [2] and energy storage (batteries or small scale pumped-storage [3]). The increasing electricity generation from variable renewable energy (VRE) sources can reduce the dependence on fossil fuels and curtail CO_2 emissions. However, each VRE source requires a supplementary flexibility solution due to its intermittency [4]. In addition, electricity demand in a building often varies a lot daily and weekly, and during holiday seasons, which increases the interest in storing energy within the building itself.

The energy consumption in elevators is usually 2–10% of the building's total energy consumption [1]. During peak hours, elevators may constitute up to 40% of the building's electricity demand [5]. The estimated daily energy consumption of elevators in New York City is 1945 MWh on weekdays, with a peak demand of 138.8 MW, and 1575 MWh during a weekend, with a peak demand of 106.0 MW [6]. Fig. 1 presents the distribution of buildings heights in New York City and the energy consumed by elevators[1].

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* Corresponding author.International Institute for Applied Systems Analysis (IIASA), Austria.

E-mail address: hunt@iiasa.ac.at (J.D. Hunt).

[1] For more details on elevator power consumption in New York City, please refer to [6].

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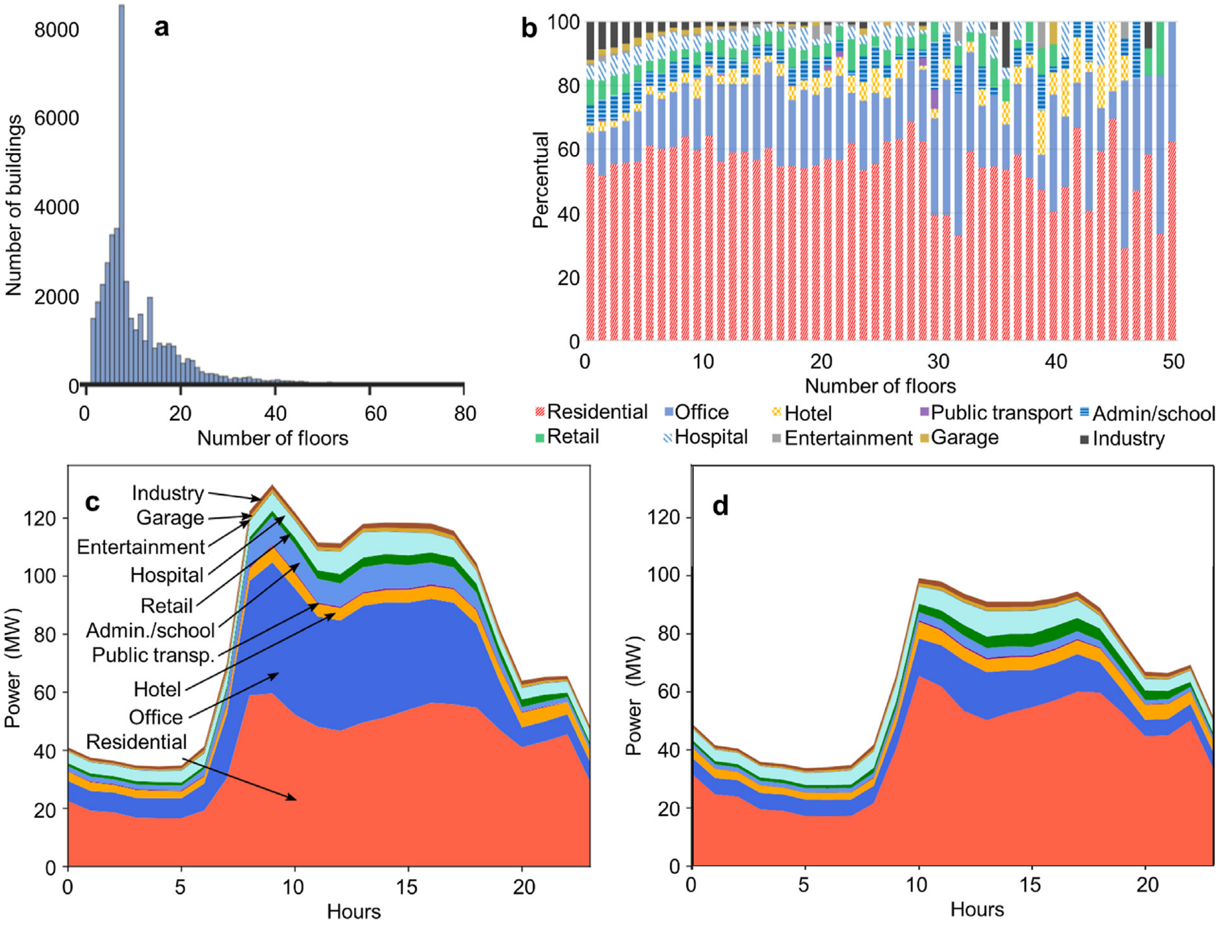


Fig. 1. New York City (a) histogram of buildings clustered by the number of floors, (b) distribution of building types as a function of the number of floors, (c) elevator power consumption by building type during a weekday and (d) during the weekend [6].

Lifts are complex systems that aim to provide quality transport services with the least costs and energy consumption. In one and a half centuries, the speed of elevators has increased 100 times [1]. New technologies and best practices involving motors, regeneration converters, control software, and optimization of counterweights or rope-free lifts can further increase the efficiency of lifts [1].

Lifts are composed of several components, as described in Ref. [7]. To achieve high and smooth acceleration offering high-quality transport services and maintaining a high overall energy efficiency, the motors are being built gearless and with regenerative brakes, which generate clean and safe electricity during descents [7]. The high-efficiency permanent-magnet synchronous gear-motor (PMSGM) has been developed for smart elevators. The efficiency of the traditional gear reducers varies between 66% and 76%, which is low. The performance and parameters of the PMSGM motor/generator have efficiencies near 92% [1,8,9]. The gain in efficiency with regenerative braking happens particularly when the elevators travel with the cars fully loaded.

Electrical energy storage (EES) alternatives for storing energy in a building are typically batteries and pumped-hydro storage (PHS) [10–13]. Batteries benefit from an ever-decreasing capital cost [14]. They will probably offer an affordable solution to store energy for intraday and daily energy variations or provide ancillary services to the grid [15–18]. However, the use of batteries to store energy in a weekly cycle might never become economically viable due to the high cost of stored energy ($/MWh) and in some cases, a high rate of losses and/or self-discharge during the day [19]. Moreover, the large-scale deployment of batteries in mobility applications and power systems raises questions related to the resource availability and sustainability of such heavy use of materials for batteries [20,21].

Pumped hydropower storage (PHS) can store large amounts of energy for weekly, monthly or seasonal cycles in potential energy stored as the mass of water in high elevations [22–26]. PHS plants are the only economically feasible option for relatively large installed storage capacities, i.e., greater than 50 or 100 MW [4,27,28]. This is because the cost of tunnels, pipelines, turbines, and generators per generation capacity will benefit from the economy of scale [29]. For example, if the diameter of the tunnel doubles, it doubles the cost of the tunnel; however, it also quadruples the amount of water that passes through the tunnel and, therefore, also the plant's capacity. Thus for PHS projects, the greater the installed capacity, the cheaper the project's installed capacity ($/MW), as shown by Ref. [30].

There is a high demand for viable technology in the market that would offer affordable long-term energy storage with a low generation capacity other than H_2 and other synthetic fuels, which suffer from a relatively low AC-to-AC efficiency and high capital cost. This paper argues that this gap could be potentially filled with a novel solution called Lift Energy Storage Technology (LEST). LEST is an EES technology that deploys an existing lift in a high-rise building to elevate a solid mass to the top of the building in the charging mode and to lower the mass generating electricity in the

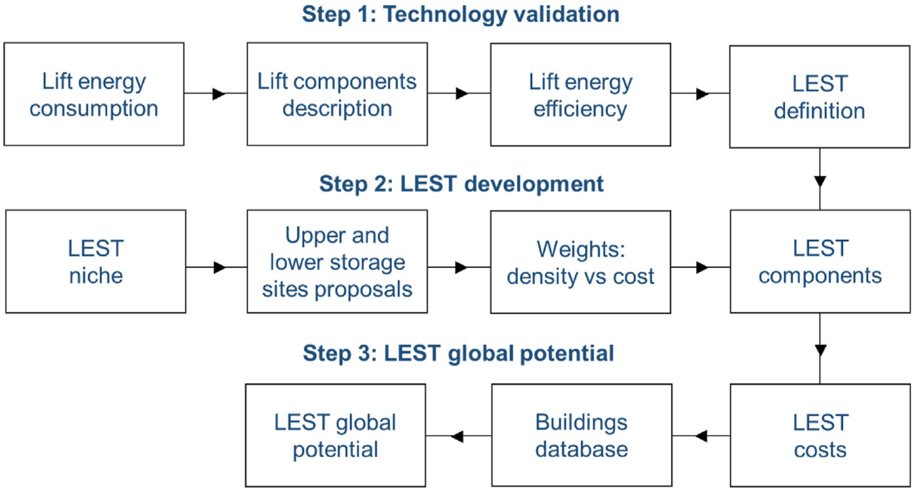


Fig. 2. Lift Energy Storage Technology methodological framework.

discharge mode. Lift technology is very mature and has been applied widely everywhere. The main interference of LEST with the existing technology is that the lift would also be used to generate electricity when lowering the elevation of the mass.

Several companies are investing in gravitational energy storage, a technology for storing potential energy with solid materials at different elevations. Energy Vault offers a head difference by building and dismantling a high tower made of concrete blocks. The disadvantage of this technology is that the head difference between the lower and upper storage sites is relatively low; it also requires great precision when constructing the 'concrete tower', which can deteriorate in time [31,32]. Another solution proposes using existing mine shafts with large heads to store potential energy [33–37]. There are also proposals for using train tracks to carry a concrete mass from the lower to the upper storage site [38–41]. Apart from having to construct rail tracks, the weight of the train itself is almost equal to the weight of the concrete block, which results in larger energy losses. The slope of the train tracks also reduces the total power output compared to a vertical descent, as proposed in this paper [42]. A similar alternative that has received much attention lately is the possibility of electricity generation with Electric Truck Hydropower [43]. Reference [44] presents a review of EES technologies, including the gravel energy storage technology [45], and others [46], which are similar to the technology presented in this paper.

To fill this existing gap for a decentralized energy storage solution in urban environments with weekly cycles, this paper proposes LEST as an innovative energy storage approach. It also shows that gravitational energy storage technologies are particularly interesting for long-term energy storage (weekly storage cycles) in systems with small energy storage demand. Furthermore, the LEST design proposed in this paper has been developed by the authors. The remaining content of this paper is structured as follows. Section 2 discusses the methods, while Section 3 presents the results. Section 4 discusses the proposed technology, and Section 5 concludes the paper.

2. Methodology

Fig. 2 presents the methodological framework implemented to assess the LEST proposed in this paper. Step 1 consists of validating the technology, analyzing the overall contribution of elevators in the building, describing the components and the efficiency of conventional lifts, and defining the proposed LEST. Step 2 consists of developing the LEST, finding its niches for energy storage services, such as installed capacity and storage cycles, proposing different types of lower and upper storage sites, and analyzing different storage material densities and costs and other system components. Step 3 consists of estimating the LEST cost, finding a global building database, and estimating the global potential for LEST.

2.1. Lift Energy Storage Technology (LEST)

LEST links two storage sites, one located on the bottom of a tall building (lower storage site) and the other at the top of the same

Table 1
Possible alternatives for the upper and lower storage sites.

Storage site	Type	Description
Upper and Lower	Empty apartments	Empty apartments can be accessed autonomously by the transport device carrying the containers, which also deposits them in a way whereby all the storage potential can be utilized.
	Occupied apartments	Utilized apartments can be accessed autonomously by the transport device carrying the containers, which can also deposit them in a way that does not disturb the function of the apartment.
	Corridors	If the use of corridors does not impede the passage of people, corridors can be used to store the containers.
	Swimming pools	In this case, the containers are filled with water. A small pump will be required to pump water from the pool to the container.
Upper	Building roof	The building roof often has spare space that can be used to store the containers. Note that the top section of the roof cannot be accessed in some buildings because the lift does not reach it.
	Tuned mass damper	A tuned mass damper is a heavy object on the top of high buildings that absorbs vibrations from high wind or earthquakes. The autonomous trailers with filled containers can move to the top of the tower to provide tuned mass damper services.
Lower	Garage	Vacant parking lots on the building can be used as a containers storage site.
	Hall	The hall is usually an area with plenty of spare space that can be used to store the containers.

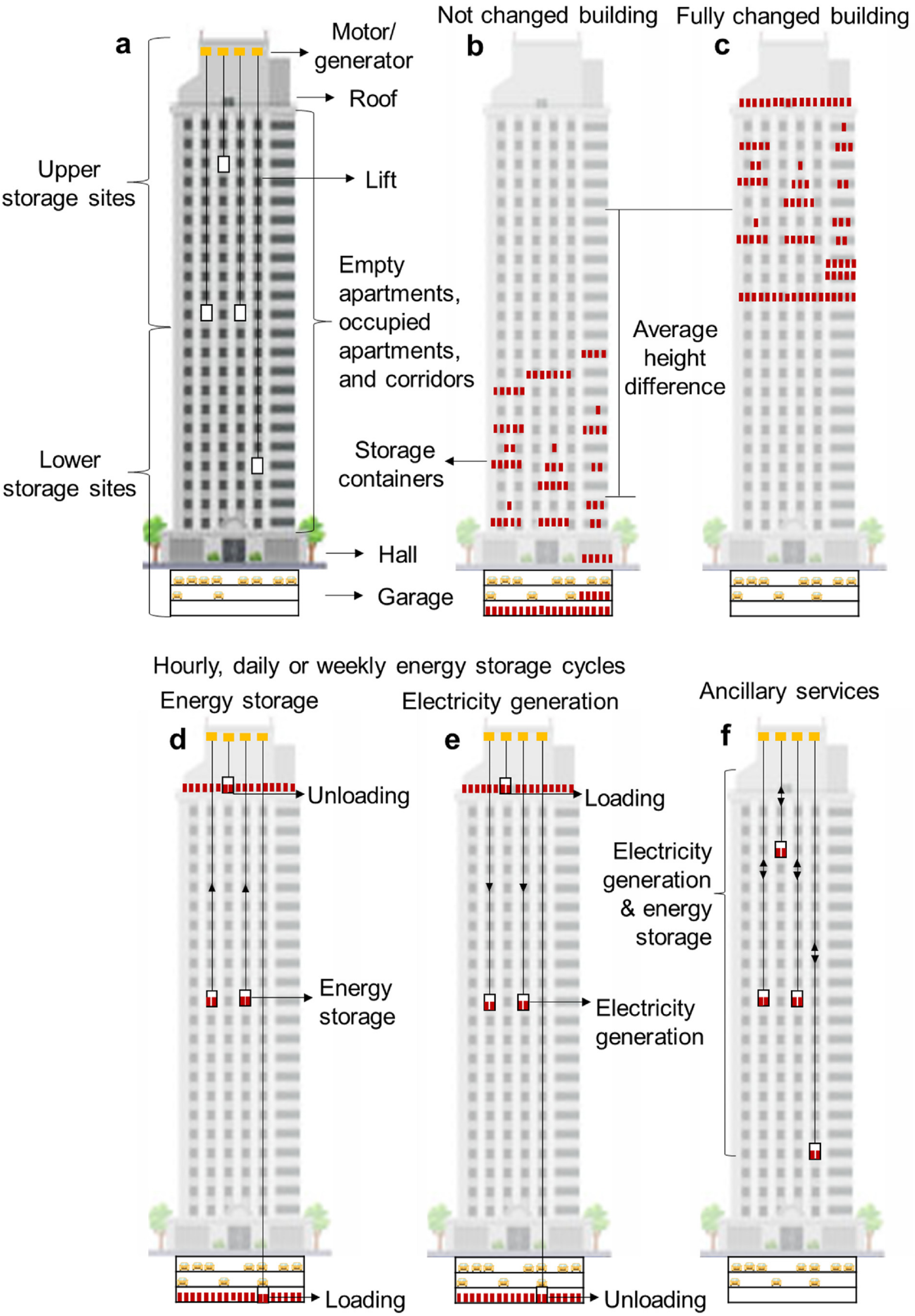


Fig. 3. Lift Energy Storage Technology (LEST) (a) system components, (b) not changed and (c) fully charged building, (d) operating on energy storage, (e) electricity generation, or (f) ancillary services mode.

building (upper storage site). Energy is stored as potential energy by elevating storage containers with an existing lift in the building from the lower storage site to the upper storage site. Electricity is then generated by lowering the storage containers from the upper to the lower storage site. An example of the proposed arrangement is presented in Table 1. The upper and lower storage sites are described in Fig. 3a,b,c. The loading and unloading of the containers into the lift is performed by an autonomous trailer that retrieves the containers from the storage site (lower or upper), enters the lift, moves up or down, leaves the lift and deposits the container in the other storage site (upper or lower, respectively) (Fig. 3d and e and Fig. 4a and b). The autonomous trailer has visual sensors to avoid hitting people when entering or leaving the lift and carrying the containers around the building (Fig. 4c). As the energy

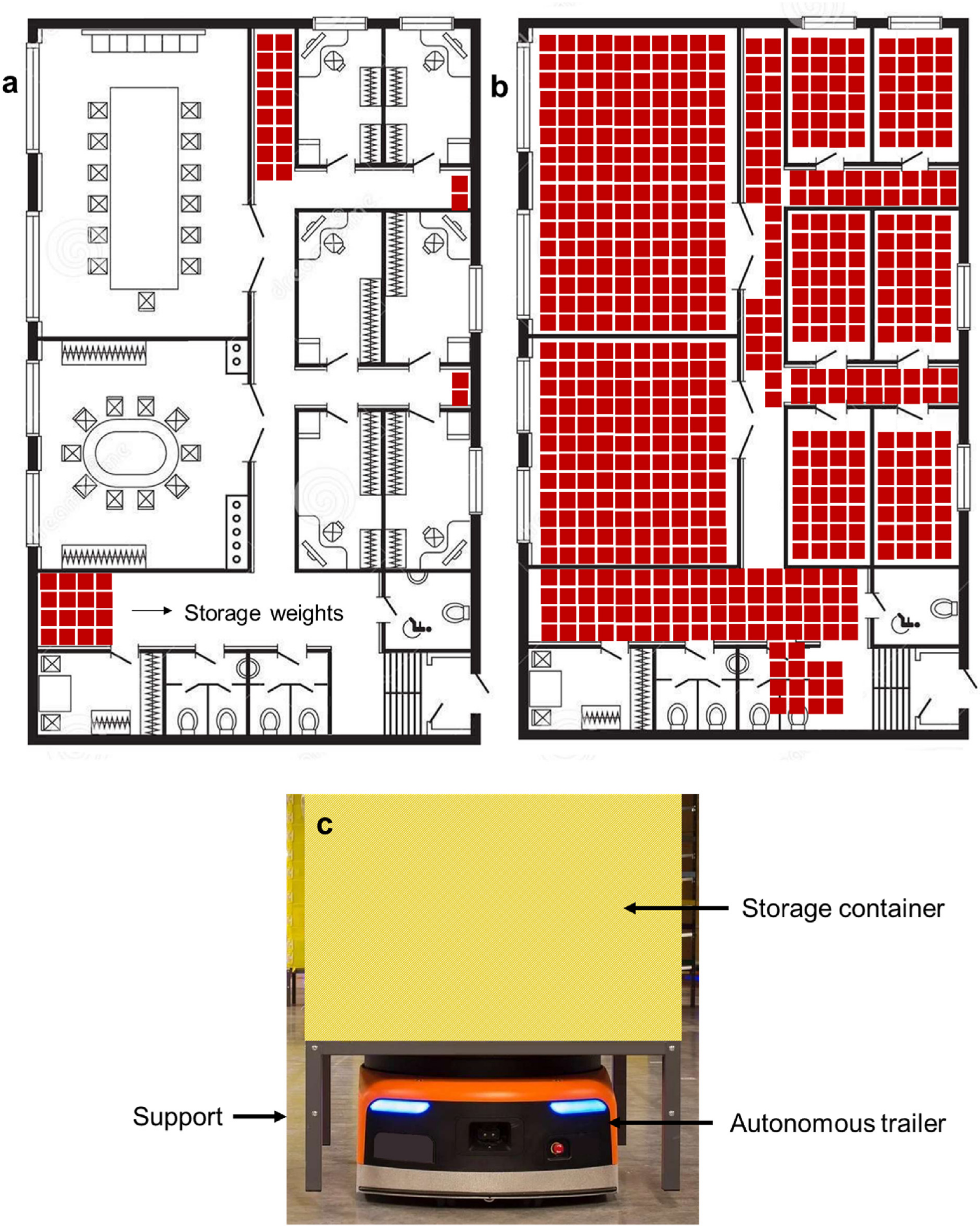


Fig. 4. (a) Occupied apartments with 36 storage containers, (b) empty apartments with 573 storage containers, (c) autonomous trailer and storage container.

requirements to move the containers horizontally with the autonomous trailer are small, they were not included in this estimate. The horizontal energy consumption will depend on the trailer, the wheels, and the flooring. Carpet flooring will significantly increase horizontal energy consumption. The storage system will record the position of the containers and run software to optimize the available storage capacity in the upper and lower storage sites. The building administration can choose to have the system operate only during periods of low lift demand to minimize the impact of the LEST system's operation on the building occupants. The lift system can vary the speed of the lift depending on the energy storage power requirements. If the power requirements are high, the lift can increase its speed; however, this will reduce the system's overall efficiency. As shown in Fig. 3f, when the lifts are not being used, such as during the night, the autonomous trailers can fill the lift with containers, and the lift can be used to provide ancillary services to the power grid by lifting and descending the mass continuously on grid requirements.

The amount of stored energy is represented by Eq. (1), which is proportional to the stored mass, the height difference between the lower and higher storage sites and the system's overall efficiency. As the head difference and the storage mass increase, the amount of energy stored in the system increases.

$$E = m \times h \times g \times e \tag{1}$$

where, E is the energy stored in the containers (J), m is the mass of the containers (kg), h is the average height difference between the upper and lower storage sites (m), g is the acceleration of gravity (m/s^2), e is the efficiency of the lift to move the containers up and down, assumed to be 80% based on [47].

The power generated by the LEST plant can be calculated with Eq. (2), where the power is equal to the energy stored in the sand or gravel divided by the time it takes to lower it. For example, the system will generate more power if the sand or gravel is lowered quickly.

$$P = \frac{E}{T} \tag{2}$$

where, P is the power generated by the LEST system (W), T is the time taken for the sand or gravel to move from the upper to the lower storage site (s). Conventional lifts are designed with a power capacity presented in Fig. 5.

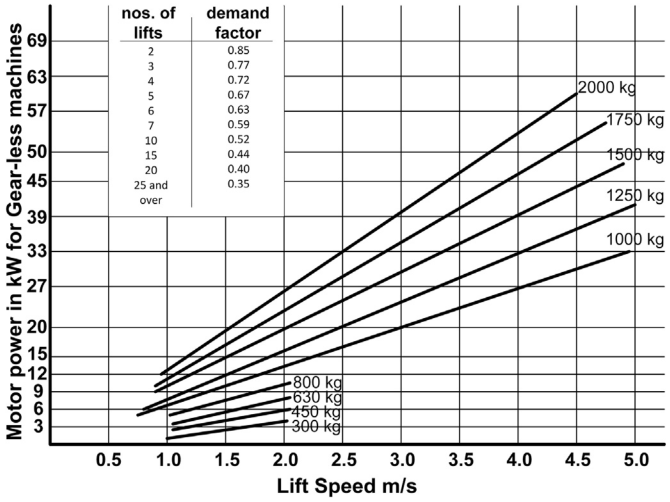


Fig. 5. Lift motor usual power consumption. Updated for quality based on Ref. [48].

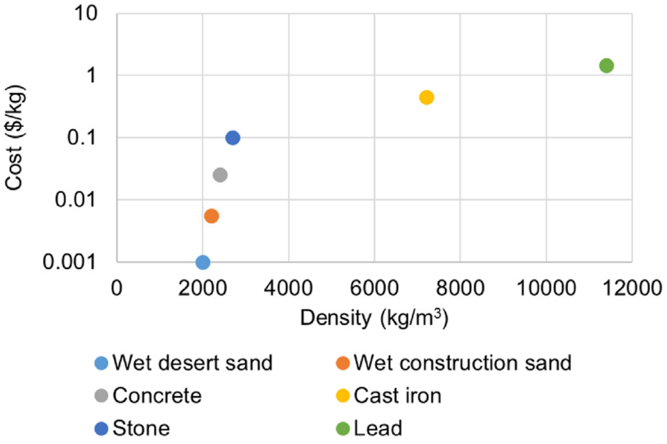


Fig. 6. Density and costs comparison of different materials [49–53].

3. Results

The storage media used in the proposed design will depend on the available space and the returns from the energy storage service. For example, if the cost of storage space is low, then a mixture of sand and water could be a good solution. On the other hand, if the cost of storage space is high, then materials with higher density might be applied. The density and the costs of several storage media have been compared and presented in Fig. 6 [49–53].

Table 2 presents a comparison of different operation arrangements for LEST, assuming systems with 5000 or 50,000 storage containers with dimensions of 0.5 × 0.5 × 2 m, filled with wet desert sand with a density of 2000 kg/m^3 and weight of 1 ton (the usual weight limit of lifts are shown in Fig. 5). The number of storage containers varies significantly with the ceiling bearing capacity of the building, further discussed in the discussion section. The storage cycle in days is estimated by assuming an average power generation capacity of 30 kW in the buildings' lifts (0.545/24/0.03 = 0.76). The generation capacity factor of the lift is low, as half of the time, the lift will be storing energy and the other half generating electricity. Also, during electricity generation mode, the lift must move up and down to generate electricity. In other words, the lift goes up twice and down twice in a storage cycle. Assuming the lift operates 70% of the time storing energy, the capacity factor of the system is 17.5%. A building with 5000 containers and a 50 m average height difference has an energy storage capacity of 545 kWh (5000 × 50 × 0.8 × 9.81 × 1000/1000/60/60 = 545 kWh), which is equivalent to the energy storage of an electric truck [54]. Note that the number of lifts in the building can increase significantly if the lifts are rope-free, as described in the discussion section. A LEST with a higher average height difference will offer a higher potential for energy storage and a longer storage cycle.

As Table 2 depicts, different operational arrangements could result in energy storage cycles of a day, weeks, or a month. The LEST

Table 2
Comparison of different arrangements for LEST.

Storage containers (tons)	Average height difference (m)	Long-term energy storage (MWh)	Storage cycle (Days)
5000	50	0.55	0.76
	100	1.09	1.51
	300	2.18	3.03
50,000	50	5.45	7.57
	100	10.90	15.14
	300	21.80	30.28

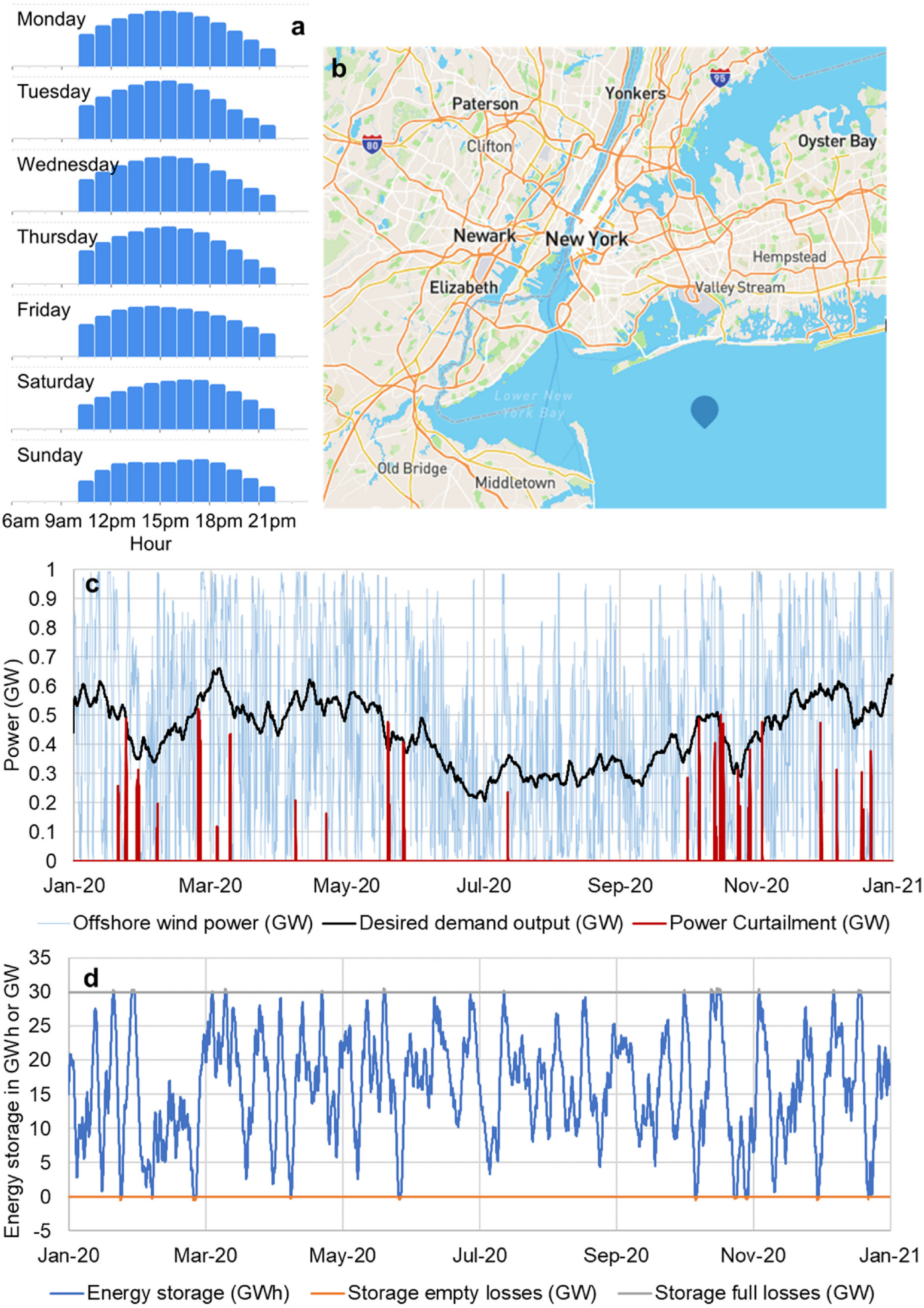


Fig. 7. A proposed operational scenario for LEST to store offshore wind power near New York City, USA. (a) Estimated average lift usage in the Empire States Building during the week [56], (b) proposed location of the offshore wind power plant [55], (c) wind power, electricity demand and energy losses (in GW), (d) energy storage (GWh) energy losses in (GW).

design and operation should focus on long-term storage cycles (weekly or monthly) since batteries can provide short-term energy storage more reliably, cheaply, and efficiently. However, if the demand mini grid's demand exceeds its peak generation capacity or if there is an excess of electricity generation in the grid, which the batteries are not able to store, the LEST could be used to complement the short-term energy storage requirements of the system.

With the intent of reproducing the operational scenario of LEST, we proposed the use of an offshore wind power plant near New York City at 40.4685 latitude and −73.7722 longitude [55], presented in Fig. 7b, with an installed capacity of 1 GW to supply the demand for electricity in tall buildings in New York City, as shown in Fig. 7c. The desired electricity generation resulting from the combined operation of the off-shore wind power plant and the LEST systems consists of the average wind power generation of one week ahead before the hour under analysis. The wind generation profile of the location uses data from the Renewable Ninja site [55]. Fig. 7a shows the visitor frequency in the Empire States building during the week. This is used to estimate when the lifts are available to be used to store energy. However, as the scenario intends to test for long-term energy storage, the daily variation in energy demand is assumed to be balanced with an auxiliary battery system in the building. The LEST system proposed has a storage capacity of 30 GWh and an initial charge of 15 GWh. To reach this storage capacity, 2752 buildings with 50,000 storage containers, each with an average height difference of 100 m would be required. As shown in Fig. 7d, the LEST operation focuses on storing energy mainly in weekly cycles, as it is designed to operate. Fig. 7c shows energy losses because the energy storage system does not have enough storage capacity to store all excess offshore wind generation. These offshore wind power curtailments are only equivalent to 2% of the total offshore wind power generation.

This paper assumes that the lift installed already has regenerative braking capabilities and the cost for renting the space to store the containers in the upper and lower storage sites is zero. Thus, the only cost requirements are the containers, the material selected to increase the mass of the containers, and the autonomous trailers (Table 3). The building used to exemplify the cost of the system has 5000 storage containers, with an average height difference of 100 m. The cost for energy storage is estimated at 64 USD/kWh. The higher the height difference between the lower and upper storage sites, the cheaper it is to store energy with LEST. Another benefit of LEST is that the lifetime of the container and material (79% of the total cost) is longer than 30 years. The lifetime of the autonomous trailer (21% of the total cost) is 5 years.

4. Discussion

This paper argues that LEST could fill the gap for decentralized energy storage technologies with weekly energy storage cycles. See Fig. 8 for LEST with MGES [58], batteries, PHS, ammonia and hydrogen. This figure focuses on long-term energy storage solutions [59] and the limits to batteries for short energy solutions. For more details on technologies with short-term storage cycles, refer to Refs. [60–66]. The results can be useful for decision makers and energy planners to understand the possible cost-benefits of this storage system compared to other alternatives.

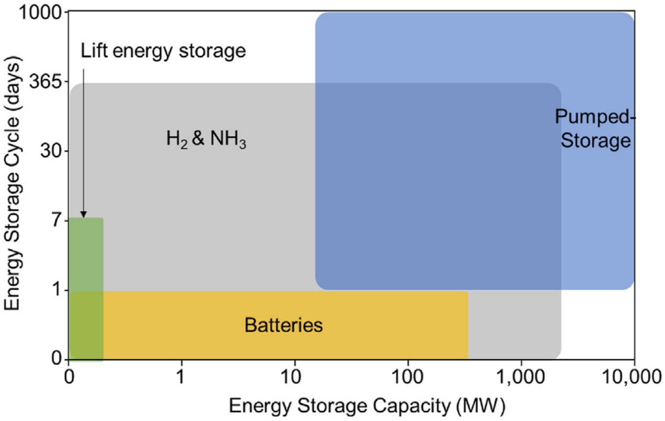


Fig. 8. Comparative illustration of long-term energy storage technologies (LES, PHS, hydrogen and ammonia) and short-term energy storage (batteries), showing their respective energy storage cycle and installed capacities.

A significant limitation for LEST, which has not been considered in this work, is the ceiling bearing capacity of the building. Buildings and their floors are designed to serve specific purposes. If the purpose of a given building is defined, engineers will follow a building code that will specify requirements regarding, for example, the floor load capacity. This is usually presented in pounds per square foot or kilograms per square meter. It is rather unlikely that buildings in the past have been designed with the idea that they might serve as energy storage facilities in the future. In this work, an assumption was made that the floor load capacity is sufficient to bear the additional weight of the storage blocks in each building. For implementation purposes, it is mandatory to evaluate the local potential by considering the ceiling bearing capacity of the building.

To minimize swaying, developers put giant counterweights called tuned mass dampers (TMD) near the top of skyscrapers. A TMD is a giant ball made of steel or concrete that weighs anywhere from 300 to 800 tons, and it's usually suspended in the building using springs and pistons. The autonomous trailers with containers also function as a tuned mass damper, moving from one side to the other to counterbalance the tower's movement in high winds or during an earthquake. As a high-rise building does not support 500 trailers for LEST, autonomous trailers from surrounding buildings that do not have issues with high wind speeds or earthquakes can move to a nearby tall building to provide tuned mass damper

Table 3
Cost estimate for LEST.

Type	Description	Cost
Container	Containers with 0.5 × 0.5 × 2 m dimensions used to store the weight material. The cost of each container is 10 USD. 5000 containers cost 50,000 USD	50,000 USD
Material	The material selected for energy storage is desert sand and water, with a cost of 1 USD/ton at the cost of 5000 USD [53].	5000 USD
Autonomous trailer	The system is assumed to have 10 autonomous trailers. Each trailer costs 1500 USD [57].	15,000 USD
Total cost	Assuming 5000 containers with an average generation head of 100 m, the cost of the LEST energy storage system is 70,000 USD.	70,000 USD
Energy storage costs	The energy storage cost is 70,000 USD and the storage capacity of 1090 kWh. This results in a cost of 64 USD/kWh. Battery costs are 120 USD/kWh. Varying the average height different from 300 to 50, the storage cost varies from 21 to 128 USD/kWh.	64 USD/kWh

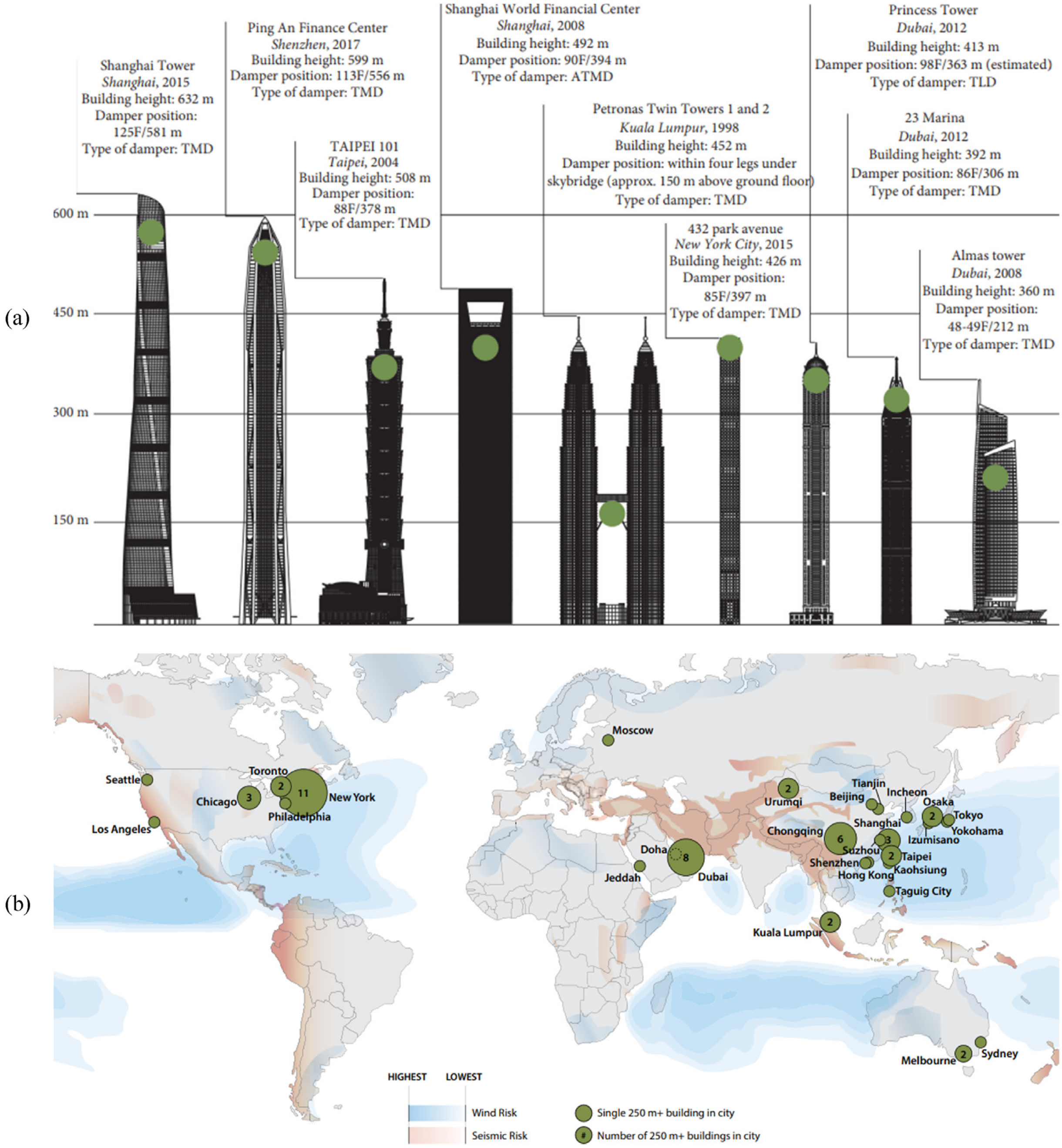


Fig. 9. (a) Examples of tuned mass dampers in high-rise buildings [68], (b) world map of the number of buildings higher than 250 m [69].

service. Fig. 9a presents examples of tuned mass dampers in high-rise buildings. Fig. 9b is a world map with the number of buildings higher than 250 m in a city. LEST is also particularly interesting in China ghost towns. There are several ghost towns where the lifts could be used as energy storage devices. A review of ghost cities in China can be seen in Ref. [67]. In some cases, the investors do not rent empty apartments because they want to be flexible to sell the flat any time they get a good price. So, LEST can be a good application for such empty flats.

ThyssenKrupp developed the Multi elevator, which does not use ropes (Fig. 10). Instead, it uses magnetic force to raise and lower the lifts [70,71]. This allows the lift to move vertically, horizontally and diagonally [72]. It is particularly interesting for high-rise buildings because several lifts can travel up or down simultaneously in the same shaft. This significantly reduces the number of shafts required in the building, increasing by up to 50% the space available for residential or office space in the building. This technology is particularly interesting for LEST because: (i) as there are several lifts in the same shaft, the acceleration and speed of the lift are significantly reduced, which increases the overall efficiency of the system (ii) the high number of lifts being raising or lowered at the same time provides a relatively constant supply of electricity, (iii) eliminating the ropes and counterweights of conventional elevators also decreases the mass of the elevator by 50%, further increasing the efficiency of the system [73].

The global potential of LEST can be estimated considering account the existing buildings. We have combined the available online information regarding high-rise buildings' location and height

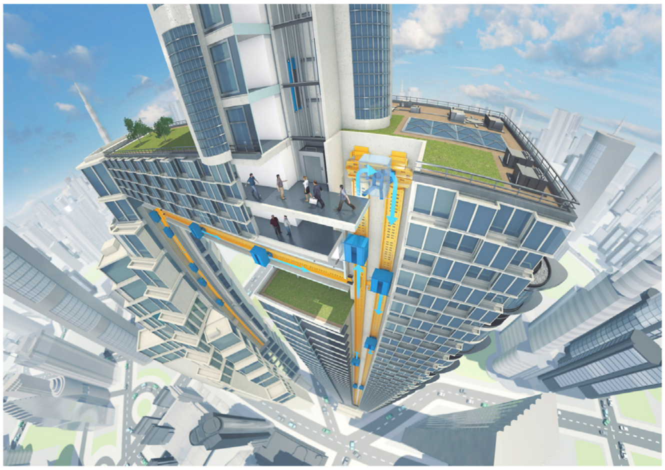
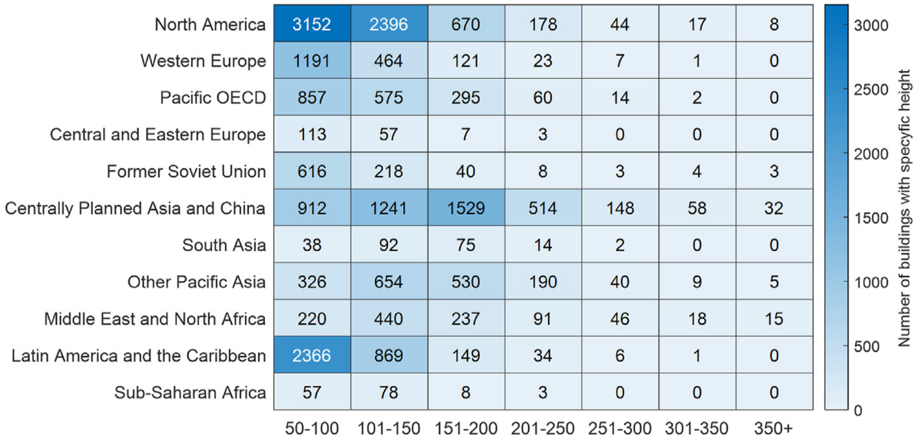


Fig. 10. ThyssenKrupp Multi elevator, the first rope-free elevator globally [74].

from the following organizations [75,76]. In our analysis, only buildings with heights exceeding 50 m were considered. The database starts with Burj Khalifa in Dubai (828 m) and ends with Wills Eye Hospital Walnut Towers in Philadelphia (53.25 m). In total, the database consists of 22,585 buildings distributed globally. Fig. 11 presents the spatial (regions) and height class distribution of buildings within the mentioned database. The mean height of considered buildings is ~120 m, and in general, the largest number of buildings can be found in North America and Asia. The number of buildings is slightly lower than in the considered database as some countries are not included in none of the mentioned regions.

To evaluate the global potential, we have followed the procedure described in Section 2. We made a conservative assumption that each building could withstand (both in terms of space and structure) the mass of 5000 containers. It has also been assumed that the average height is equal to the building height – in some cases, it might lead to an overestimation as some buildings have tall spires not suitable as an upper storage site. At the same time, our calculations neglect the potential increase in average height if deep basements are used as lower storage sites. The results are presented in Fig. 12. The coordinates of buildings have been rounded up to the



	50-100	101-150	151-200	201-250	251-300	301-350	350+
North America	3152	2396	670	178	44	17	8
Western Europe	1191	464	121	23	7	1	0
Pacific OECD	857	575	295	60	14	2	0
Central and Eastern Europe	113	57	7	3	0	0	0
Former Soviet Union	616	218	40	8	3	4	3
Centrally Planned Asia and China	912	1241	1529	514	148	58	32
South Asia	38	92	75	14	2	0	0
Other Pacific Asia	326	654	530	190	40	9	5
Middle East and North Africa	220	440	237	91	46	18	15
Latin America and the Caribbean	2366	869	149	34	6	1	0
Sub-Saharan Africa	57	78	8	3	0	0	0

Fig. 11. Number of buildings (colorbar) with specific heights (horizontal axis - ranges are in meters) in selected regions (vertical axis). Regions and countries belonging to them are based on [77].

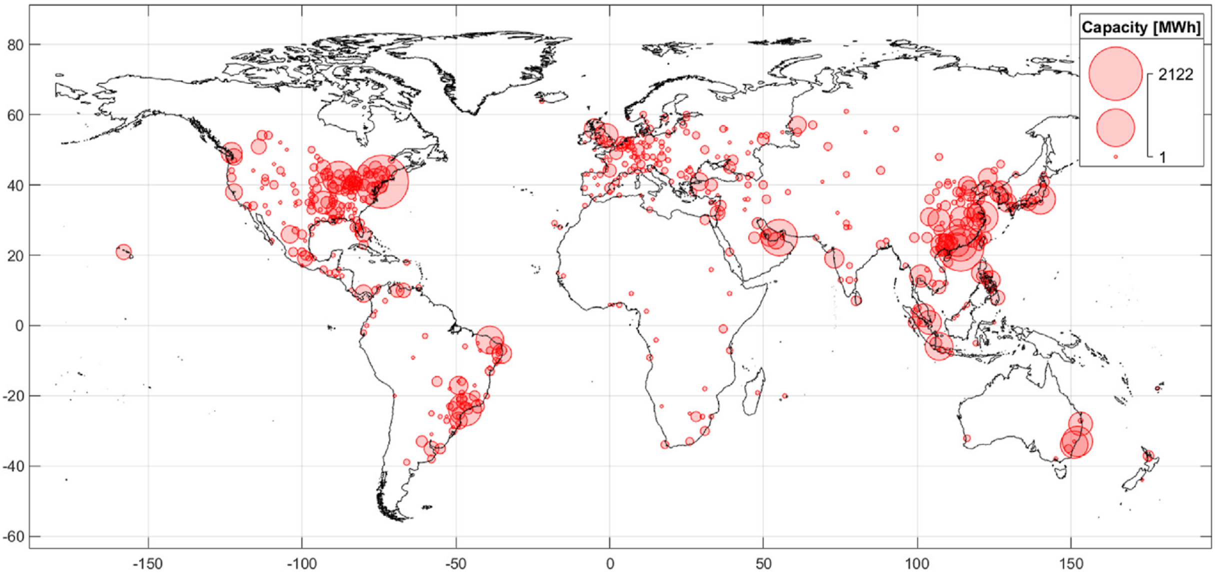


Fig. 12. Lift energy storage technology - global potential.

closest integer and grouped. Hence buildings near each other are presented together. The global potential was found to be 29.2 GWh, which is rounded to 30 GWh in this paper. Assuming that 50,000 containers can be stored in the buildings, this global potential rises to 300 GWh. The storage potential is proportional to the building height, hence the earlier mentioned Burj Khalifa could potentially store 9 to 90 MWh. The LEST storage potential in the USA sums up to 6.5 to 65 GWh and to 7.3 to 73 GWh in China.

Future directions for the further development of LEST are: (i) run experiments on an existing building with regenerative braking lifts to estimate the efficiency of LEST with different motor/generators and operational modes, such as acceleration and speed, (ii) implement LEST in a building to reduce the overall electricity costs of the building, or store energy from intermittent renewable energy sources, (iii) analyses the benefits and challenges of providing decentralized ancillary services with LEST, (vi) compare LEST with flywheels, (v) design buildings from scratch to optimize their use for energy storage with LEST.

5. Conclusion

This paper concludes that Lift Energy Storage Technology could be a viable alternative to long-term energy storage in high-rise buildings. LEST could be designed to store energy for long-term time scales (a week) to generate a small but constant amount of energy for a long time. This small but constant electricity generation could be combined with other storage technologies, such as batteries, to balance the short-term variations of electricity demand, solar and wind generation.

This paper estimates the cost of installed capacity energy storage cost of LEST to be 62 USD/kWh, assuming an average height difference between the upper and lower reservoirs of 100 m. The cost of LEST with an average height difference of 300 m is 21 USD/kWh, whereas an average height difference of 50 m costs 128 USD/kWh. This is half of the cost of storing energy with batteries. The power generation will depend on the existing numbers of lifts in the considered buildings. The technical lifetime of the system can vary from 20 to 30 years. The higher the height difference between the lower and upper storage sites, the lower the project's cost. LEST systems are particularly interesting in buildings with rope-free elevators, and they can also provide tuned mass damper services on the top of very high buildings.

LEST systems are particularly interesting during the night when most lifts are not being used, as the autonomous trailers can continue to fill the lifts with containers to provide ancillary services to the power grid. This is particularly interesting because the demand for ancillary services will increase with the increase in solar and wind power generation, the demand for ancillary services will increase. Having ancillary solutions close to the final demand significantly optimizes frequency and load balancing, improving the quality of the electricity supplied by the grid.

The global storage potential for the technology varies from 30 to 300 GWh, mainly in metropolitan areas with tall buildings, such as New York, Chicago, Philadelphia, Seattle, Los Angeles, Hawaii and Toronto in North America, Dubai and Doha in the Middle East, Beijing, Shanghai, Hong Kong, Tokyo, Kuala Lumpur and Singapore in Asia, and Sydney and Melbourne in Australia. Even though small islands in the Caribbean, Indonesia, the Philippines, and the Pacific Islands don't usually have very many high-rise buildings, these would be more favorable locations for LEST, due to their higher electricity costs and smaller energy storage demand. LEST can serve as a decentralized urban energy storage solution to balance weekly variations in electricity supply from wind and solar sources and demand variations.

Author contributions

Conceptualization, J.H., J.J.; methodology, B.Z., A.N; formal analysis, P·B.; investigation, R.B; data curation, P.D.; writing—original draft preparation, J.H.; writing—review and editing, J.J.; visualization, J.H.; project administration, W·F., N·C., K.R; funding acquisition, A.N.; resources, K.R.; software, P.D. All authors have read and agreed to the published version of the manuscript.

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.

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