Feasibility of Gravity Batteries in Residential Homes: A Case Study

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ABSTRACT

Sustainable energy generation and storage are key factors in the transformation of society towards a carbon-free future. While great progress has been made in the development of renewable energy generation systems, there is still a mismatch between the global energy supply and demand. Renewable energy sources, such as solar and wind energy, are subject to variable efficiencies that depend heavily on local weather conditions. Thus, energy storage is necessary for a sustainable energy grid to meet the demand of high usage phases during periods of lower energy production. Although many systems currently depend on chemical batteries for energy storage, these systems face issues regarding the limited availability of materials needed for fabrication as well as the energy intensive production and recycling processes tied to such systems. Thus, the feasibility, scalability, and use cases of simplified and environmentally friendly alternative energy storage options must be investigated. Subsequently, a feasibility study on the use of a gravity battery as a form of domestic energy storage was conducted in Purdue University's DC Nanogrid House, an ongoing project that aims to convert a residential property to run solely on DC power whilst operating predominantly independent of the grid. Gravity batteries store energy in the form of potential by lifting a weight using a motor-winch combination. When needed, the battery is discharged by lowering the weight and utilizing a generator to convert the potential energy back into electricity. This is an attractive form of energy storage for its simplicity and longevity without the need for chemical components. In the present paper, the energy consumption data of the DC Nanogrid House was first analyzed to set goals for the required storage capacity of the system, followed by the development of an initial design that was later modeled using CAD. This design went through a techno-economic analysis and was optimized to meet the building and safety specifications. The case study and the techno-economic analysis performed were all used in determining that while gravity batteries continue to show great promise in industry, the insufficient volumetric energy density and efficiency of the systems make the technology currently unviable to be effectively utilized on the residential scale.

1. INTRODUCTION

Residential scale energy production around the globe is on the rise, increasing the pressure to develop cost efficient and long-term storage systems. Lithium-ion (Li-ion) battery systems currently dominate this market due to their outstanding efficiency and dropping prices. The price of high efficiency (85-90%) Li-ion batteries has already dropped 20% since 2013 (Parrera and Petel, 2019). However, due to their composition, li-ion batteries suffer when left in a partially charged state. The unpredictability of daily energy consumption makes it almost impossible to ensure the battery is fully discharged at the end of each day. If left partially charged, the maximum capacity of Li-ion batteries can drop between 10-15% in a year (Angenendt et al., 2018). Although Li-ion batteries currently dominate the market, their longevity and environmental concerns leave much room for innovation in residential energy storage.

Although Li-ion batteries are currently the most widespread option for residential energy storage, it is important to note the environmental impact due to their manufacturing process. For every ton of lithium mined, approximately half a million liters of water are used which can ultimately poison the water reservoirs (Tedesco, 2023) due to the energy required for the mining process coming from CO2 emitting fossil fuels (Crawford et al., 2022). Furthermore, a meta-analysis of existing data was conducted (Peters et al., 2017), concluding that on average, 1 kWh of storage capacity in Li-ion batteries is associated with roughly 74 g of CO_2 emissions. In all, the harmful environmental impact of such lithium batteries counteracts the eco-friendly goals of non-carbon residential energy production.

The rising awareness of the harmful effect of fossil fuels on the environment has fueled the motivation for research into the field of alternative energy solutions. One such solution, a solid energy storage system, or gravity battery, is currently on the rise in recent years for its eco-friendly ability to efficiently store and release energy in a cost-effective manner. As a rather novel concept, very little is known of the capability of gravity batteries, leaving many skeptical if the technology is even viable. Despite these limitations, there is still promise for gravity battery systems on the industrial scale, with one source noting that by factoring in initial capital and operation costs over an extended period gravity storage can be cheaper than lithium batteries (O'Grady, 2021). This price decrease may not necessarily be associated with diminished performance, however, as in the case of a gravity storage system developed by Charlie Blair, claiming to have the ability to generate nearly 10 MWh of power if installed in one of the deepest mines in the UK, spanning 3,000 feet (914 meters) (Bowoto et al., 2021). Thus, although a relatively new technology, the future of gravity batteries remains bright according to experts within the field.

To evaluate the potential usage of gravity battery in residential houses, a feasibility study was conducted in Purdue University's DC Nanogrid House, an ongoing project that aims to convert a residential property to run solely on DC power whilst operating predominantly independent of the grid. The electrical energy for the house is provided by a photovoltaic system installed on the roof. Given the inherent disparity between the peak energy production time and the peak consumption time of the house, electrical energy storage (EES) is needed to store excess energy and provide it when needed, which makes the DC Nanogrid House a practical case study for energy storage technologies. In this paper, the energy consumption data of the DC Nanogrid House was first analyzed to set goals for the required storage capacity of the system, followed by the development of an initial design that was later modeled using CAD. The techno-economic analysis as well as the building safety specifications are discussed.

2. METHODOLOGY

2.1 DC Nanogrid House Energy Consumption

To begin the analysis of a gravity battery in a residential home, energy consumption data from the DC Nanogrid House was collected and analyzed from December 2022 to February 2023. The data was sorted hourly and averaged to better understand the energy needs throughout the day, as shown in Figure 1.

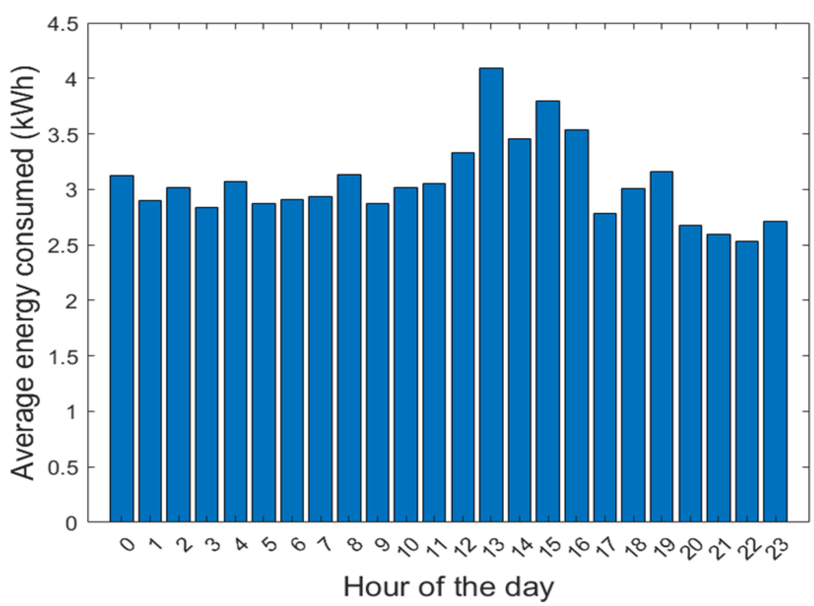

Figure 1: Average energy profile over one day for the DC Nanogrid House.

From this data, it is evident that energy usage is highest during the afternoon hours, and lowest during late evening. Further classifying the hours into “daytime” and “nighttime” hours according to routines of the residents and average sunrise and sunset times, the difference in energy consumption becomes even more clear.

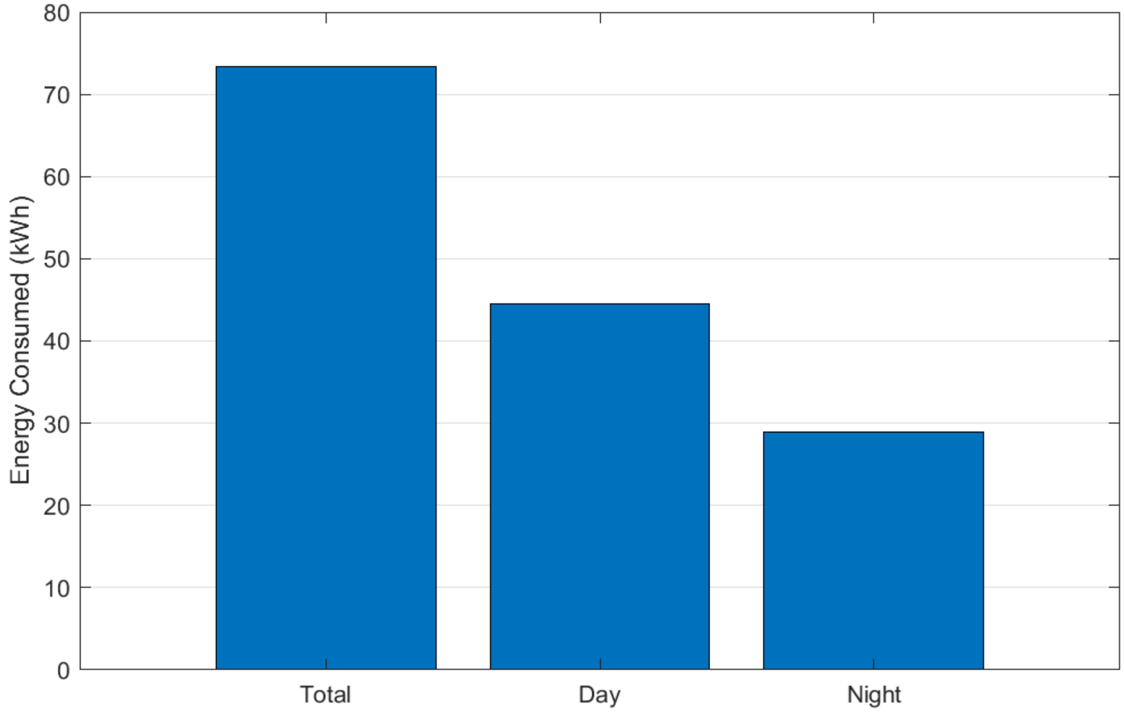

Figure 2: Average daytime and nighttime consumption of the DC Nanogrid House.

Figure 2 shows the great disparity in total energy usage between the daytime (8 a.m. and 9 p.m.), in which most of the energy can be generated by the solar panels, and nighttime (between 9 p.m. and 8 a.m.), when little to no energy is able to be generated. Moreover, showing that even with less energy being used during the night compared with that of the day, the night still accounts for nearly 40% of the total energy usage due to the relatively large base load related to the AC and heating system, highlighting the importance of an energy storage system being needed to accommodate the needs of the house.

2.2 Gravity Battery Design

Given their nature of using gravitational potential energy, the storage capacity of gravity batteries increases linearly as the height of travel increases. To maximize the storage capacity of this residential system the team aimed to utilize the existing layout of the DC Nanogrid house and design a system that would span from the lowest to the highest point of the house. The proposed battery system runs from the floor of the basement to the attic.

To reduce complexity and ensure feasibility, the team proposed that the final design of the gravity battery resemble that of a modern-day elevator system. As such, a motor-pulley system was chosen to be able to handle the load of the system. Furthermore, guide rollers are to be attached to the concrete weight allowing it to ride on carbon steel guide rails within the shaft. Polyurethane buffers are to be placed on the bottom of the shaft to help slow the descent of the weight at the bottom of the shaft. An overspeed governor was selected as the primary safety mechanism, with the ability to immediately stop the freefall of the weight in case of emergency.

The weight required for this project is much heavier than residential houses can support on their own. To aid in this, a truss was designed to support the weight like an elevator shaft. The ability of a truss to distribute large loads and remain rigid made it a perfect option for this application. A preliminary CAD model was developed along with a model of the DC Nanogrid House floorplans to aid in visualizing the placement and relative size of the gravity battery system.

Figure 3: Preliminary CAD Model.

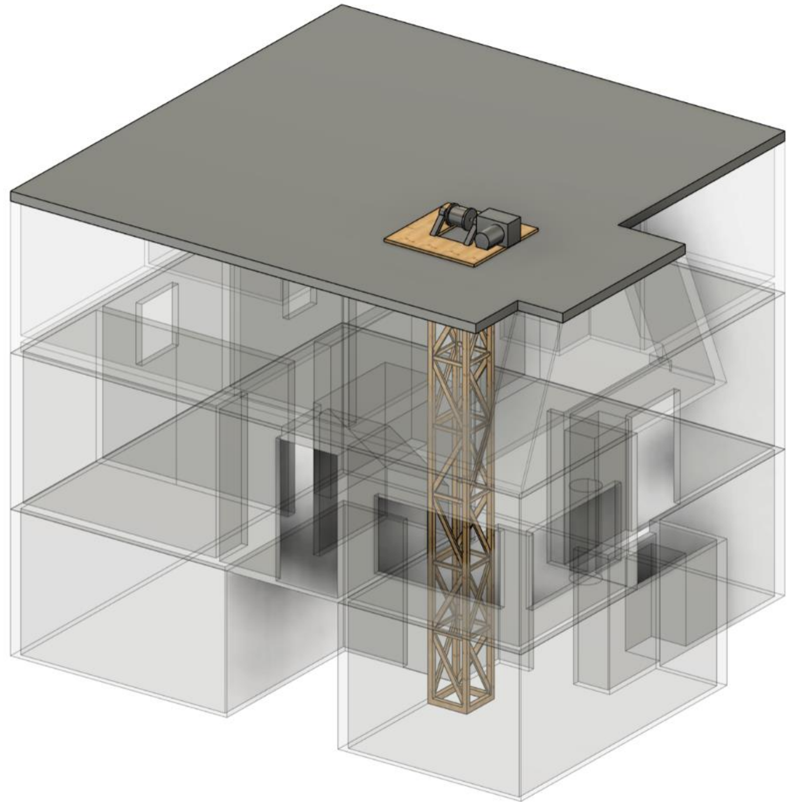

Figure 4: Potential position of the gravity battery in the DC Nanogrid House (CAD Model).

To further communicate the design intent, the weight, motor generator, and gearbox were represented as primitive shapes. The first floor of the DC house will also have access to a window looking into the truss, which currently sits approximately 2.4 meters (8 feet) from the base of the truss and basement floor. By modeling the gravity battery inside of the home, dimensions could be better estimated, and constraints could better be visualized to assist in the calculation of possible energy storage capabilities.

The stability of the designed truss plays a crucial role in the support of the weight that is to be suspended. As such, selection of the material to build the truss out of was needed to predict expected cost and ensure the stability of the system. The following table outlines six of the most popular woods on the market, comparing their compressive strength to their costs per unit.

Table 1: Truss Material Selection.

Wood Type	**Compressive Strength (MPa)**	**Price ($ / 4” × 4” x 10’)**	**Price ($ / 2” × 4” × 10’**
Douglas Fir	49-51	$22.69	$4.69
Ponderosa Pine	36-36.5	N/A	$10
White Fir	18	$15.60	N/A
Southern Yellow Pine	52-66.8	$17.58	$5.42
Western Red Cedar	17.2	$80	$30.85

Moreover, southern yellow pine was selected as the best option to be used as the material for the truss for its high compressive strength and low cost. Since the main objective of the truss is to support vertical loading, the outside vertical beams must carry the main load. As such, 4×4 dimensional lumber (89 mm × 89 mm) was proposed for the vertical members and 2×4 dimensional lumber (38 mm × 89 mm) for the diagonal and horizontal members that do not bear as much load. The truss pieces are to be held together using standard mending plates.

2.3 Weight Specification

Deciding on the specifications for the weight is a crucial portion of this project as it defines how much energy storage is expected and influences design decisions of other aspects of the project. For example, the safety system, and the motor and generator selection are both dependent on the size, shape, and material of the weight itself. The design of the truss provides constraints for the width, depth and shape of the weight, but the height and material of the weight needed to be optimized.

Due to their high density and relatively low cost, solid steel and high-density concrete make great options to be used as the weight in gravity battery systems. Steel is the heavier option with a density of roughly 8,000 $\mathrm{kg/m^3}$, as compared to high-density concrete's 6,200 $\mathrm{kg/m^3}$. However, working with steel has several notable drawbacks. First, steel is much more expensive than concrete. Secondly the transportation of a steel block of this size would require significant effort to position the weight within new and existing houses. Although lighter than steel, high-density concrete has lots of attractive attributes for this application as well as for possible future considerations. The most attractive aspect of concrete relative to steel is the price. In general, concrete tends to cost much less than steel. Another benefit of using concrete over steel is its convenience. Unlike large amounts of steel, dry concrete can be easily purchased and transported straight from a hardware retailer. Additionally, a mold could be constructed on site, eliminating the need for expensive and time-consuming transport.

With the material selected, the team could move forward with the optimization of the mass of the weight. With the width and depth of the weight constrained by the inner dimensions of the truss, the mass of the weight could only be changed by adjusting the height. In general, a heavier weight can store more potential energy. However, making the weight heavier makes it taller, sacrificing travel height of the overall system. Equation 1 describes the relationship of potential energy capacity, as a function of mass. Potential energy (kJ) is a function of mass (kg), gravitational constant ($\mathrm{m/s^2}$) and the max height the weight travels (m). The last term in the equation represents the max travel height which is the total height of the shaft minus the height of the weight itself. The height of the weight is expressed as a function of its mass (kg) by dividing mass by the concrete density ($\mathrm{kg/m^3}$), width (m) and length (m).

$$PE = m \cdot g \cdot [h - \left(\frac{m}{\rho w l}\right)] \tag{1}$$

The relationship described in equation (1) can be seen plotted in Figure 5 below.

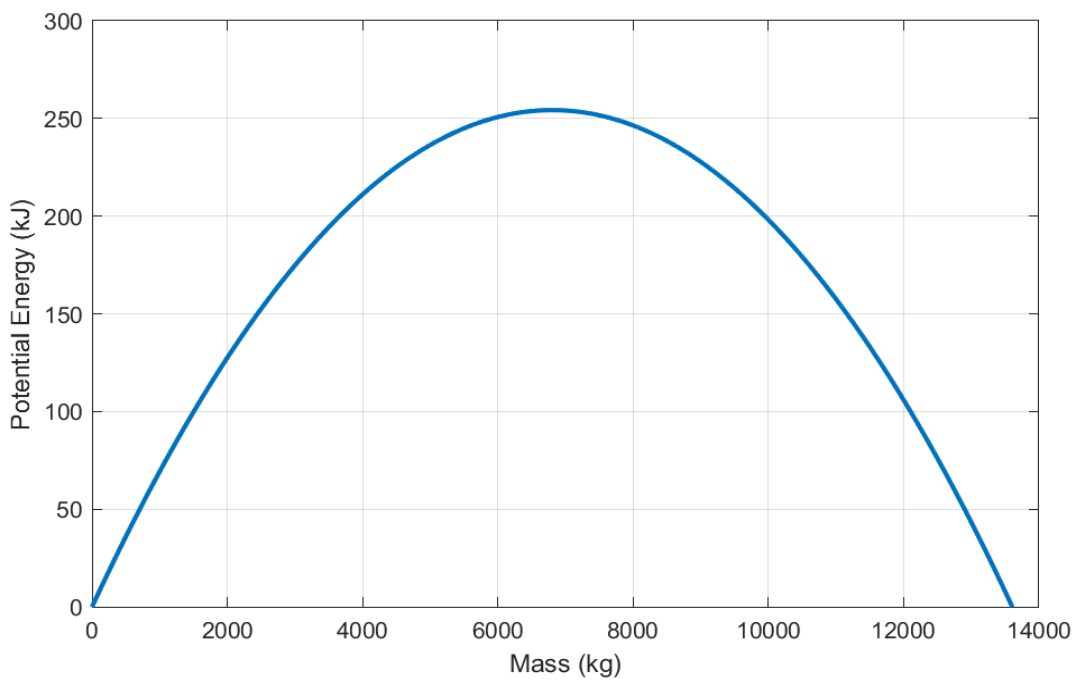

Figure 5*:* Specific energy vs. mass.

The maximum value of this graph suggests that a weight with mass of 6,236 kilograms would be able to store the most potential energy in our system (256 kJ). It is also important to consider the energy density of the weight. Since mass decreases the travel height the energy density (amount of energy stored per unit mass) also decreases with more mass. Specific energy density is important to consider because it represents how cost effective the system is as adding more mass increases the price. Equation (2) calculates specific energy density (kJ/kg) by dividing the potential energy as function of mass (equation 1) by mass in kg.

$$ED = \frac{m \cdot g \cdot [h - \left(\frac{m}{\rho \cdot w \cdot l}\right)]}{m} = \frac{PE}{m} \tag{2}$$

This relatonship can be seen plotted below.

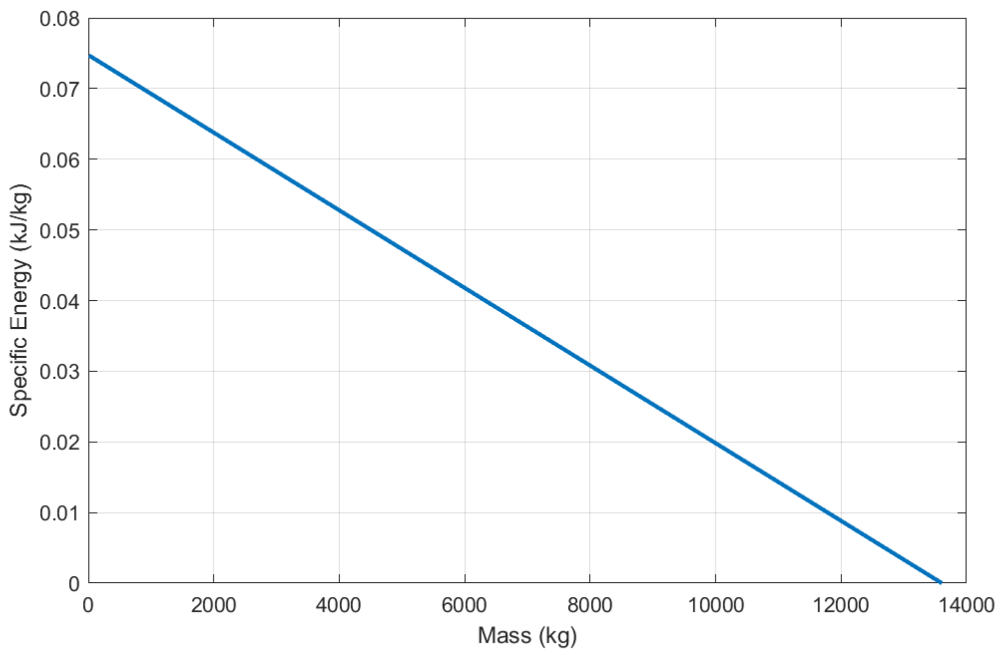

Figure 6: Potential Energy Density vs. Mass.

This plot shows that increasing mass (and storage capacity) comes at the sacrifice of cost efficiency. Observing the plots in Figure 5 and Figure 6 it becomes obvious that selecting a mass that would optimize the specific energy of the system would not optimize the potential energy capacity of the system. Ultimately, an optimization using weighted objectives was preformed to decide on an optimal sized mass for the system. The team decided to prioritize the specific energy of the system twice as much as the overall storage capacity. This decision was fueled by the intention of parameterizing a system that would be both feasible and sought after for future residential use. Using this methodology, a weight with a mass of roughly 2,078 kg was selected. The complete specs of the weight are detailed in Table 2 below.

Table 2: Final weight specifications.

Material	High Density Concrete
Density (kg/m^3)	4805.54
Height (m)	1.164
Volume (m^3)	0.433
Mass (kg)	2078.965
Mass (tones)	2.292
Cost (US$)	169.75

The implementation of springs or other devices to increase the energy capacity was explored. However, during the design phase it was clear that the addition of springs would add negligible energy capacity to a gravity battery, sized for domestic application. Without the implementation of extremely large and expensive springs that would require the complete redesign of the system to accommodate them.

3. TECHNO-ECONOMIC ANALYSIS

A cost analysis was conducted to estimate the financial effort needed to construct a gravity battery system within the DC Nanogrid House. The total cost of such a project can vary drastically depending on the materials selected, maintenance and labor costs and the overall design of the system. The following section briefly discusses the different components that contribute to the overall cost of constructing a gravity battery in a residential home. The prices listed are approximations based on the intended design and are representative of the market prices of selected parts at the time of investigation.

3.1 Shaft and Weight Costs

As previously discussed, a wooden shaft was selected to aid in the support of the system, as seen in Figure 3. The cost of the wooden truss is summarized in the table below.

Table 3: Shaft and Weight Bill of Materials.

Item	Part	Quantity	Unit Price* ($)	Cost ($)
1	4 × 4 × 10’ Southern Pine Beam	17	17.58	298.66
2	2 × 4 × 10’ Southern Pine Beam	12	5.42	65.04
3	5” × 5” Prolonged Truss Plate	54	2.99	161.46
4	3” × 6” Steel Mending Plate	2	1.38	2.76
Total Cost			**527.92**	

With this, the team estimates that the cost of the shaft would be roughly $530.

3.3 Pulley System Costs

Once the overall structure of the system was designed costs were estimated for the shaft, the team moved toward estimating the cost for the system responsible for raising and lowering the weight. This system would require a motor driven pulley system to hoist the weight up along guide rails. The team estimated the cost of such a system based on the proposed weight, with the results being reported below.

Table 4: Pulley System Bill of Materials.

Item	Part	Quantity	Unit Price* ($)	Cost ($)
1	Concrete Weight	1	169.75	169.75
2	Winch/Motor/Generator System	1	445.00	445.00
3	1500 kg Pulley	3	284.26	852.78
4	Carbon Steel T-Bar Guide Rail	2	177.50	355.00
5	Guide Roller	2	150.00	300.00
Total Cost			**2122.53**	

The cost of the weight was heavily dependent on the density requirements of the project. In all, the team estimated that the total cost of the pulley system would be approximately $2120, with the pulleys accounting for approximately 40% of these costs.

3.4 Safety System Costs

Having been designed for a residential home, safety considerations were a top priority. The team decided the best way to mitigate risks is to design the safety system of the battery to mimic that of a modern-day elevator system with the implementation of an overspeed governor. This device is to be placed at the top of the shaft, having the ability to detect and halt freefalling motion of the device in the case of emergency. Additionally, much like elevator systems, a polyurethane buffer is to be placed at the floor of the shaft to halt the motion of the weight before reaching the basement floor. Price estimates for the overspeed governor and buffer can be seen in the table below.

Table 5: Safety System Bill of Materials.

Item	**Part**	**Quantity**	**Unit Price* ($)**	**Cost ($)**
1	Overspeed Governor	1	1	5000.00
2	Polyurethane Buffer	1	49.99	49.99
Total Cost			**5049.99**	

The safety system for the battery is projected to cost approximately $5050 with the overspeed governor accounting for most of this cost.

3.5 Maintenance and Labor Costs

The cost of maintenance for a gravity battery can vary largely between elevator systems, ranging anywhere from $800 - $1400 (Home Elevators, n.d.). Furthermore, the cost of installation is another consideration and can cost anywhere from $3600-$5000 (Home Elevator Network (n.d.).

3.6 Total Costs and Energy Capacity

After estimating the cost of each subassembly within the project, the team composed a comprehensive bill of materials to help estimate the total cost of a gravity battery in a residential home.

Table 6: Total Gravity Battery System Bill of Materials.

Item	**Part**	**Quantity**	**Unit Price* ($)**	**Cost ($)**
1	4 × 4 × 10’ Southern Pine Beam	17	17.58	298.66
2	2 × 4 × 10’ Southern Pine Beam	12	5.42	65.04
3	5” x 5” Prolonged Truss Plate	54	2.99	161.46
4	3” × 6” Steel Mending Plate	2	1.38	2.76
5	Overspeed Governor	1	5,000	5000.00
6	Winch/Motor/Generator System	1	445.00	445.00
7	1500 kg Pulley	3	284.26	852.78
8	Carbon Steel T-Bar Guide Rail	2	177.50	355.00
9	Guide Roller	2	150.00	300.00
10	Polyurethane Buffer	1	49.99	49.99
11	Concrete Weight	1	169.75	169.75
Total Cost ($)			**7700.44**	

The team concluded that the final design would cost approximately $7,700 in parts and at least $3600 in installation and would have the capacity to store approximately 171 kJ/47.5 Wh, the equivalent of approximately 12 AA batteries. With the price of one kWh in Indiana at just $0.16 in 2024 (energysage, 2024), it would take more than 1.4 million cycles of the gravity battery to break even without the consideration of maintenance costs. With such low energy capacity and high costs of installation, it is evident that the proposed design is not economically justified.

Observing the data shown in Figure 5, the maximum energy potential that can be stored in the designed shaft, without considering the optimization of the energy density of the system is approximately 256 kJ/71.11 Wh. While increasing the size of the shaft would increase the energy capacity of the system it could only do so with a maximum linear increase with the volume of the weight. To achieve an energy capacity of even 1 kWh would require a weight of at least nearly 8 times the designed volume, reaching over 3 m^3 in size. Accompanied by the fact that this would only equate to approximately 40% of the energy capacity needed to power the DC Nanogrid House during the least demanding hour on average, it soon became clear that the proposed system would fall well short of the energy demands required to act as the sole energy storage device in the house.

4. CONCLUSION

The capabilities of gravity batteries as large-scale energy stores are still largely unknown and untapped. Emerging companies that specialize in the research and development of gravity battery systems have shown much progress in recent years which has led to the popularization of the technology.

After researching, planning, and designing a gravity battery within a residential home, a cost estimate was performed, and the final cost of the proposed system was estimated to be over $11,000. Thus, it was concluded that the capital needed to construct a gravity battery far surpasses the cost of current market benchmarks that achieve similar or superior energy storage capabilities. This observation makes the project unrealistic without severe changes to the proposed design. Nevertheless, the practical energy density of a gravity battery is far less than alternative systems currently available. Weights with a larger density were considered, but the increased capital needed to obtain materials with such densities far outweigh the potential energy storage gains of such a system.

While the concept of gravity batteries appears to be a viable source of energy storage on the larger scale, in practice the low energy density achieved, unavoidable energy losses produced, and massive capital required to construct such a system currently makes the technology unattractive for residential applications. More generally, current designs for gravitational potential energy systems seem to be an unviable source of energy storage for small scale utilization.

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NOMENCLATURE

CAD	computer aided design	(-)
DC	direct current	(-)
ED	specific energy density	(J/m)
EES	electrical energy storage	(-)
g	gravitational constant	(m/s^2)
h	height	(m)
h	length	(m)
Li-ion	lithium ion	(-)
m	mass	(kg)
PE	potential energy	(J)
w	width	(m)
ρ	density	(kg/m^3)