Algorithm and Optimization Model for Energy Storage Using Vertically Stacked Blocks

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This work was supported in part by the Boysen-TU Dresden-Research Training Group with Open Access Funding provided by the Publication Fund of the TU Dresden.

ABSTRACT With increasing adoption of supply-dependent energy sources like renewables, Energy Storage Systems (ESS) are needed to remove the gap between energy demand and supply at different time periods. During daylight there is an excess of energy supply and during the night, it drops considerably. This paper focuses on the possibility of energy storage in vertically stacked blocks as suggested by recent startups. An algorithm is proposed based on conceptual constraints, to allow for removal and storage of excess electrical energy in the form of gravitational potential energy. To improve these results further, the concepts of wasted energy and unmet demand are used to develop a new mathematical model which aims to minimize the maximum unmet demand in all time periods using lowering and stacking of blocks at specific locations. Simulation results show that for time periods up to a week long, this storage system is able to shift blocks stored in a tower of vertically stacked blocks to reduce unmet demand significantly. This is augmented by storing extra energy from a photovoltaic system, taking account of stochasticity and temporal variability. The authors therefore conclude based on a sensitivity analysis that this system and its associated mathematical optimization can be feasible when scaled up to meet ancillary-level grid storage applications.

INDEX TERMS Energy storage system, gravity, mathematical modeling, optimization, sustainability.

I. INTRODUCTION Traditionally, electrical energy has been distributed in the form of an electrical grid. The grid is composed of a series of interconnected loads and generators that allow for smooth planning and distribution of electricity. The demand nodes on an electric grid, also referred to as ‘loads’ are the consumers of electrical energy. This demand is changing on an hourly basis depending on several factors such as the type of loads, number of consumers and others, a variability that is reflected in the instantaneous price of electricity, also dubbed the ‘spot’ price [1].

Owing to the ever increasing carbon emissions from burning fossil fuels, there is a push for greater reliance on renewables in the future. Renewable technologies such as solar and wind typically have lower carbon emissions. These operate at times that are typically independent of the load profile, and have a greater link to natural phenomenon such as the amount of sunlight experienced, temperature, wind speed and cloud cover [2]. As a result, their supply output has been described as intermittent and difficult to control. In instances where the grid cannot distribute the entire output from these Embedded Renewable Generation sources, the entire output has to be curtailed, a significant loss of energy [3].

Typically, demand and supply do not coincide in high renewable energy penetration scenarios, leading to the need for a way to store excess supply to fulfil excess demand at a later time. This is typically achieved using an Energy Storage System (ESS) [4]. Traditional storage systems have involved chemical reactions to convert excel electrical energy into chemical energy for use at a later time. These are typically short term storage solutions with energy storage and output highly dependent on the types of materials used in building the battery and are difficult to scale to a grid level storage system [5].
Alternate longer term, higher yield energy storage technologies available include pumped hydro storage, which utilizes surplus energy to pump water to a higher level, driving a turbine and generating electricity when it is brought down using gravity later [6]. A turbine based system can also be driven by storing compressed gas in an underground reservoir, which can be a depleted fossil fuel source or a manmade reservoir. Hydrogen is often discussed as a long term storage technique where excess energy is used to produce hydrogen in an electrolyzer, to be used in a fuel cell at a later point [7]. Surplus energy can also be stored in the form of inertia of a rotating flywheel for a medium term storage [8]. Each energy storage technology is restricted by its own constraints, typically involving energy density, costs of construction and scalability of the technology leading to the need to balance costs v. output, where output is both energy stored and duration of energy storage, along with overall system efficiency [9].

In this paper, a new mathematical model is developed for a novel ESS which is based on vertical blocks energy storage. In this ESS, excess electrical energy is stored by loading blocks in a tower format using a crane powered by solar energy. In the case of higher demand, energy is supplied from the tower by lowering blocks. The proposed mathematical model enables us to plan and schedule this ESS by optimizing the coordination of all block movements in each period of time to minimize maximum unmet demand. The paper attempts to fill a gap in the literature regarding low cost, ancillary level energy storage technologies and approaches that are scalable and installable in areas not limited by geographical features and installation complexity. It also aims to build upon recent funding acquired by commercial startups working on similar projects by proposing an optimized approach that increases the runtime of the model by balancing demand and supply over subsequent time periods.

The remainder of the paper is organized as follows: Section II briefly reviews the related research works in existing literature on energy storage systems. Section III starts with an explanation of vertical blocks energy storage system followed by the formulation of the algorithm and mathematical models. Computational results are presented in section IV along with sensitivity analysis and numerical results. Section V presents conclusions and gives suggestions for further research in this field.

II. LITERATURE REVIEW

There are multiple energy storage technologies available worldwide, each with their individual benefits, costs and constraints. Several common features and comparisons and differences between multiple energy storage options have been analyzed on both technical aspects and associated economics [10]. Other researchers have analyzed energy storage options on different scales of energy demand matching, with a greater emphasis on the theoretical background of multiple energy storage options [11]. Photovoltaic systems have variable peaks that often require some form of storage or storage to accommodate in order to design the economic feasibility. Extensive research has been done on scheduling demand-side management using mixed integer linear programming to better match supply restrictions from photovoltaic systems as an alternative approach to energy storage [12]–[14].

On a smaller level, batteries have become the most common energy storage method globally, a review of which has been compiled [15]. Several recommendations have been proposed for maximizing the battery life of these systems, given their limited number of discharge cycles [16]. An alternate approach has explored a model system utilizing compressed air in underground storage systems as a method of storing energy in a renewable heavy grid environment [17]. Furthermore, a procedure that utilizes the thermal properties of concrete as possible energy storage tools has also been proposed with variable real-world applications [18].

Using gravity for energy storage is a relatively mature idea, with a relevant patent being filed by in 1917 [19]. By using pumped water for storage at different levels, there are greater possibilities of increasing renewable energy penetration [20]. A similar system for off grid implementation has been explored and a complete technical feasibility for an island in Hong Kong has been published [21]. These technologies are highly dependent on geographical locations and subject to expensive material requirements for construction on a large scale.

In the mainstream grids, the need for larger storage systems have been discussed in detail, including some of the challenges and opportunities associated with gravity based pumped hydro storage [22]. An extensive review summarized in [23] compares many microgrid level energy storage options and concludes on the need for a novel energy storage system to incorporate a sustainable ESS with lower cost, complexity and optimal scheduling. The potential of a gravity based energy storage system coupled with a photovoltaic energy plant has been studied extensively and modelled in literature [24]. A similar design has also been proposed using abandoned mine shafts and optimal sizing of the plant has been done [25]. A commercially available application titled the ‘Advanced Rail Energy Storage System’ has been created in Nevada, with a rated energy storage of 12.5 MWh, which is based on a design previously proposed and patented [26], [27]. A commercial enterprise has recently begun operation of a demonstration prototype for a vertically stacked tower of concrete/gravel blocks under the name “Energy Vault” [28]. This tower is circular and removed blocks are stacked in a surrounding tower again, from where they are raised to store energy again.

Optimization of the energy system including energy storage is necessary to account for variations in demand and supply under different constraints to ensure cost efficiency, especially in developing countries [29]. The use of CPLEX in balancing large energy systems with energy storage options is a longstanding trend due to its powerful implementation in GAMS [30], [31]. It has been regularly used to optimize the gaps between energy production and demand by way
of incorporating energy storage through two stage robust optimizations [32]. Recent approaches in this field have used mixed integer linear programming for energy storage optimization at the household level for decentralized energy storage applications [33].

The work proposed in this paper focuses on similar design principles as some of these papers reviewed, but is more focused on improving energy storage in vertically stacked objects based on the work highlighted in literature as well as on a recently developed startup [34], [35]. This is done after conversion from intermittent primary sources (solar – chemical energy) to gravitational potential energy, which can later be converted back to electrical energy in time frames of unmet demand in the grid. Furthermore, the proposed mathematical model improves the performance of the ESS and simplified the system planning and scheduling. The Vertical Blocks Energy Storage System is designed as a long term gravity-based energy storage system and is being developed by commercial enterprises. The highlighted contributions in this field, listed in this paper are as follows:

• The paper proposes a parameter called unmet demand that reflects the gap between the energy demand at a particular hour and the energy supply from an intermittent energy source in conjunction with a storage system and then proceeds to minimize this parameter over one week by means of an optimized scheduling model.

• The authors acknowledge a gap in existing literature in the application of optimization to the stacking schedule of vertically stacked objects to minimize the gap between supply and demand from the system. This paper aims to add to the discussion regarding using dry gravity-based energy storage as opposed to other long-term storage options such as compressed gas energy storage and pumped hydro energy storage.

• As such, this paper is the first to propose in literature to store energy in vertical blocks and aims to elongate the duration of security of supply provided by stacking blocks in a particular order.

• The paper takes into account the intermittency of solar energy supply by carrying out a sensitivity analysis of different possible energy demand and supply values with the VBESS acting as a buffer between them to minimize unmet demand.

• Compared to the model discussed in [28], the authors propose an optimized energy storage mathematical model which will ensure the optimal configuration of stacking blocks both in the X-Y plane and the Z dimension. The model is optimized over a duration of 7 days and comparison to a simpler un-optimized constraints-based simulation is presented. The effect of intermittent supply and demand is considered in the optimality discussion.

III. VERTICAL BLOCKS ENERGY STORAGE SYSTEM

This section focuses on one grid scale application of energy storage by using excess energy produced from a limited solar array to supply a regular household. The gap between supply and consumption of energy is to be mitigated by storing the excess energy using a set of direct current motors to store weighted blocks on top of each other. In the advent of there being excess demand compared to availability of supply, these blocks will be lowered at constant speed, and electricity is reproduced using regenerative braking. The innovation aspect of this paper incorporates modelling blocks at different altitudes and proposing a stacking and removing algorithm that allows for the optimization of different levels in order to ensure longevity of the model, and thereby allowing for the most efficient exploitation of the possible outcomes. The authors assume storing energy in blocks weighing 1000 kg each, with cubic dimensions of 1m × 1m × 1m. These can be composed of 1.3 yd³ of compressed municipal solid waste, which can weigh the required amount if compressed in a large landfill with Best Management Practices [36]. Adding blocks is done from one corner of the grid outwards. Blocks are removed from the other three corners first, travelling inwards. This sequence is shown in Figure 1 along with possible empty and full arrangements in 5 × 5 × 5 dimension as an example.

To lift the blocks, a direct current electric overhead beam crane is proposed with a height of up to 60m, to allow for stacking up to 50m, 1m high blocks in a 5 × 5 or 10 matrix. The blocks are stacked together with no gap between individual vertical stacks. This is done to provide the structure with inherent stability. Furthermore, individual blocks would require a metal frame to increase rigidity and reduce compression in the face of applied weight from higher blocks. The location of blocks will also be recycled, with lower ones being brought to higher levels at subsequent iterations. Being One level, for the purpose of this paper, is defined as between 0 and 25 (in a 5 × 5 arrangement) or 100 (in a 10 × 10 arrangement) blocks arranged in the same height plane. If the tower has a maximum height of 50, this is referred to as 50 levels, where some levels might have more blocks than the level above. The arrangement is shown in the schematic diagram in Figure 2.

For the crane itself, a constant efficiency of 0.8 for the electric motor is assumed [37]. This can be defined as the crane converting 80% of the electrical energy input into gravitational potential energy gained when the platform is raised. This is in addition to the amount of energy supplied by the electric power drive to raise a block to a required height differential. Elastic potential energy in the cables of the crane itself is ignored. For lowering the block, the crane moves the object downwards using regenerative braking with
a constant efficiency of 0.7, which is defined as the crane converting 70% of the gravitational potential energy released by lowering the platform into electrical energy supplied by the regenerative braking [38]. This brings the round-trip theoretical efficiency of 56%.

The energy stored in a block at a particular height is calculated using the standard equation of potential energy as shown in equation (1):

\[ E_p = mgh, \]

where:
- \( E_p \) = Stored Potential Energy (J)
- \( m \) = mass (kg)
- \( g \) = acceleration due to gravity (\( N/\text{kg} \))
- \( h \) = height (m)

The proposed VBESS uses a set of a maximum 1250 and 5000 blocks, arranged in a \( 5 \times 5 \) and \( 10 \times 10 \) grid structure respectively, with individual towers limited at 50m. In reality, increasing the dimensions of this setup in the X and Y dimensions leads to a nonlinear increase in the total storage potential (see figure 3). Furthermore, the blocks are limited to a height of 50, but with sufficient structural storage and rigidity, increasing the maximum height of the blocks can result in this setup becoming a viable grid level energy storage system. The structure has one mounted overhead crane that moves parallel to the X and Y axis along the bridge and runaway beam. In cases where the deployed system is to be sized with X and Y dimensions greater than 10, multiple cranes can be installed on the same runaway beams, providing a lower cost to scale up the project. The proposed mathematical model currently assumes constant electrical losses due to the movement of the crane in the X-Y plane, however cascading multiple cranes together can reduce real world energy usage per unit due to shorter distance travel. Locating this project at landfill installations can allow for the tower to begin below ground level, thereby reducing the overall height of the system.

A. COMPARATIVE STUDY
For a \( 20 \times 20 \) structure with a block height limited at 100 blocks, the total usable energy in the system is an estimated 3.9 MWh. This will require approximately 20 tonnes of compressed landfill garbage, which can be manufactured at the cost of approximately US$2000 including 30% cost for compression and processing [39]. Additional expenditure for generators and overhead cranes can be estimated at US $30,000 for a 50kW system composed of two cranes and two generators. This brings the estimated total cost of storage to about US $30 per kWh of storage. This is similar to the energy storage cost of a commercial solution using the same principle [28]. The lifetime of this sort of a system is limited by the rigidity of the blocks and the maintenance and operation of the cranes and generators, but can be estimated to be over 20 years. For comparison, other ancillary storage technologies are summarized in Table 1.

B. UN- OPTIMIZED SIMULATION MODEL DESIGN
To simulate energy storage in a tower of blocks, an algorithm has been devised that allows for balancing energy storage with supply and demand. For any given time instant, the difference between net energy consumption and supply is referred to as the net energy. If net energy is positive, it reflects greater demand than supply and requires taking off blocks from the best possible locations in the tower to generate electricity. If net energy is negative, extra energy is available and the best possible locations needs to be designed to lift additional blocks from the ground to be stored at those locations. The algorithm for such transactions is summarized in figure 4.

At any given iteration, if net energy is positive it allows for calling a subroutine to remove blocks. The designed algorithm places some structural limits on the tower such as...
ensuring that no block is available to be removed that will result in the next highest-level block becoming lower than the blocks surrounding it. This ensures that access to any block from a crane is achieved sideways from outside the model at that altitude and no block needs to be lifted up to be brought out of the model. The same limit is applied when blocks are being stored. This is achieved in both cases by defining layers of the model (when viewing from the top). Outer layers are picked first for removing blocks and inner layers are given priority when storing blocks, as shown in Figure 5. When removing blocks, layer 2 is given priority unless all blocks at the top levels of layer 2 are lower than the highest level of layer 1 or lower than required energy demand, whereas when storing blocks, level 1 is given priority and layer 2 is only considered if layer 1 is higher than available energy. The constraints are programmed into a recursive instruction set using Matlab 2019b.

### Table 1. ESSs comparison [40], [41].

| Name & Specifications | Costs |
|-----------------------|-------|
| Advance Rail Energy System (ARES) | $800/kW |
| Charging Capacity: 57MW | 4 MWh |
| Discharging Capacity: 44MW | storage: |
| Storage Capacity: 250 GWh | Est. $30,000 |
| Lifetime: 40+ years Efficiency: 75-86% | |
| Severely limited by geography | |
| Very complicated installation | |
| Pumped Hydro Storage (PHS) | $600-2000 |
| Energy density: | /kW |
| 0.5-1.5 Wh/l | $6-100 |
| 0.5-1.5 Wh/kg | /kWh |
| Self-discharge: 0.005-0.02% /day | 4 MWh |
| Lifetime: 30+ years Efficiency: 70-80% | storage: |
| Storage Capacity: est. 1000 MW | Est. |
| Severely limited by geography – require natural underground storage | $24,000-1000m |
| Medium | 40,000 |
| complexity installation | 80,000 |
| Compressed Air Energy Storage (CAES) | 700-1000 $ |
| Discharge Capacity: 110 MW | /kW |
| Storage Capacity: 28600MWh | 40-80 $/kWh |
| Lifetime: 30+ years Efficiency: 34.5% | 4 MWh |
| Severely limited by geography – require natural underground storage | storage: |
| Medium | Est. |
| complexity installation | $40,000 |
| Vanadium Flow Batteries (VFB) | 600 |
| Energy Density | 1500 $/kWh |
| 16-60 W h/l 10-85 W h/kg | 150 |
| Discharge Capacity: | 1000 $/kWh |
| 0.005-15 MW Storage Capacity: 0.010-10 MWh | 4 MWh |
| Self-discharge rate: 0.2-0.24% /day | $600,000 to 4,000,000 |
| Lifetime: 5-15 years Efficiency: 57 to 90% | |
| High complexity due to installation of membrane separation chamber | |
| Can be installed anywhere | |
| Gravity Power Storage [25], [42] | 1000 $/kW |
| Energy Density: | 40 $/kWh |
| 0.5-1.5 Wh/l 0.5-1.5 Wh/kg | 4 MWh |
| Discharge Capacity: 40-1000 MW | storage: |
| Storage Capacity: 8.5-200 MWh | Est. $40,000 |
| Lifetime: 30+ years Efficiency: 75-80% | |
| Gravity Power Module unit needs to be placed in a site with a stable morphology | |
| Medium complexity due to closed water loop | |
C. MATHEMATICAL MODEL DESIGN

To solve this problem, a mathematical model for optimizing the proposed vertical blocks energy storage system (VBESS) is formulated. In this model, the objective function is minimizing the maximum value of unmet demand in all time periods. Unmet demand is defined as the difference in the hourly energy available from solar panels and energy storage in vertical blocks versus the demand of energy at the same timestamp. Thus, the effectiveness of the ESS can be estimated by calculating the amount of energy demand that could be met by shifting energy from a high supply time period to a high demand period. A zero value of unmet demand suggests that during the optimization period, sufficient energy was stored within the blocks to be able to completely fulfill the total demand. For this purpose, different operational limitations of the system should be interpreted as the model constraints which are further divided into two categories.

The first category of these constraints is related to picking up and locating blocks in the storage tower. For example: it is not possible to pick up a block from an inner level when there are blocks in the upper levels or directly overhead. This is done by ensuring that the variable $B_{kt}$, number of existing blocks in level $k$ in time period $t$, for a level $k$ is always more than or equal to the $B_{kt}$ for all higher levels. Furthermore, it should be considered that the number blocks which are removed ($XR_{kt}$) or stored ($XL_{kt}$) have to follow the sequence which described in section 3. The model also depends on a self-defined initial condition of a full tower, defined by parameter $I$ for all $k$, when $t$ is set as 1. There should be a block in the lower level, and a vacant position wherever a block is going to be located when the tower is being reconstructed as well.

The second category of constraints is associated with different demand and supply values. Using these equations, the model matches the local demand to the highest possible degree and stores excess supply in the best possible combination of stored blocks in the tower. In this manner, a sequence is implemented that plans the removal of blocks from the tower, to create electricity using regenerative braking when the demand from the consumer is higher than the available solar energy (represented by variable $S_{t}^{-}$), and the stacking of blocks on the tower at different heights during times when solar energy is abundant (represented by the variable $S_{t}^{+}$). This is done in a specific and optimized sequence, that takes into account the overall difference between demand and supply over long time horizons, instead of being dependent on instantaneous situations. This is achieved by constantly monitoring the variables $S_{t}^{+}$ and $S_{t}^{-}$, which represents the excess energy available from solar, and the unmet demand in at other time periods respectively. Modeling indices, parameters and decision variables are defined in Table 2.

According to the pattern shown in the figure 6, blocks are stored and removed starting from one corner [X, Y Position (3,1)] of the shape. At times of energy surplus, blocks are stored in the opposite sequence, starting from X, Y Position (1,3) and then diagonally moving across the level. For the purpose of this computation, energy required for moving the blocks horizontally at a constant vertical level is considered negligible.

The mathematical model for the VBESS problem can now be developed to provide a detail plan for energy release and storage to minimize the maximum unmet demand by drawing a schedule for picking up from and stacking blocks in the VBESS tower. The model is formulated as follow:

$$\min : Z$$  \hspace{1cm} (2)

$$S_{t}^{-} \leq Z \quad \forall t \in T$$  \hspace{1cm} (3)

$$TD_{t} - TS_{t} - S_{t}^{-} + S_{t}^{+} = 0 \quad \forall t \in T$$  \hspace{1cm} (4)

### Table 2. Notations.

| Sets | Description |
|------|-------------|
| $K$  | Set of the tower levels, $k \in K$ |
| $T$  | Set of time periods, $t \in T$, $t=1, 2, ..., TH$ |

| Parameters | Description |
|------------|-------------|
| $d_{t}$   | Local demand in time period $t$ |
| $p_{t}$   | Solar cells energy supply in time period $t$ |
| $l_{k}$   | Required energy to locate a block in level $k$ |
| $r_{k}$   | Released energy from dropping a block from level $k$ |
| $id$      | Length of the tower |
| $jd$      | Width of the tower |
| $M$       | A big number |
| $ML$      | Max number of the tower levels |
| $I$       | Number of full levels at starting time |
| $TH$      | Max Planning Horizon hour |

| Variables | Description |
|-----------|-------------|
| $TD_{t}$ | Total Demand |
| $TS_{t}$ | Total Supply |
| $CE_{t}$ | Energy required to raise and place a block at a particular level |
| $SE_{t}$ | Energy released/produced by the system when a block is lowered |
| $XL_{kt}$| An Integer variable shows number of stacked blocks to level $k$ in time period $t$ according to the storing pattern (see section 3). |
| $XR_{kt}$| An integer variable shows number of released blocks from level $k$ in time period $t$ according to the releasing pattern (see section 3). |
| $B_{kt}$ | An integer variable shows number of existing blocks in level $k$ in time period $t$ |
| $S_{t}^{+}$ | Excess supply in time period $t$ |
| $S_{t}^{-}$ | Unmet demand in time period $t$ |
The objective function (2) minimizes the maximum unmet demand in the planning horizon, calculated subject to constraint (3). The value of unmet demand and available supply in each time period is determined in equation (4). Constraints (4) and (5), compute required energy to locate blocks in tower and released energy by releasing blocks in each time period respectively. Total demand and supply are computed in equations (7) and (8) respectively and constraint (9) ensures that consumed energy to place blocks in the tower in each time period should be provided by excess solar energy supply in the same time period. Constraints (10) and (11) ensure that the number of existing blocks in each level is equal to the number of blocks from the last time period plus the number of placed blocks and minus number of released ones. Constraints (12) to (14) express a special condition for the first level of tower. Constraint (15) allows the model to start with a complete pre-constructed tower. Constraints (16), and (17) are associated with picking up and placing the blocks.

\[
\begin{align*}
\sum_{k=1}^{K} l_k X_{kl,t} &= CE_t \quad \forall t \in T \\
\sum_{k=1}^{K} r_k X_{kl+1,t} &= SE_t \quad \forall t \in T \\
\sum_{k=1}^{K} d_t + CE_t &= TD_t \quad \forall t \in T \\
p_t + TS_t &= TS_t \quad \forall t \in T \\
CE_t &\leq p_t - d_t \quad \forall t \in T \\
B_{kl,t} &= B_{k,t-1} + X_{kl,t} - X_{kl+1,t} \quad \forall t \in T \text{ and } k \in K > 1 \\
B_{k,t} &= B_{k,0} - X_{k,1} \quad \forall t = 1 \text{ and } k \in K > 1 \\
X_{l,t} &= 0 \quad \forall t \in T \\
X_{R_{l,t}} &= 0 \quad \forall t \in T \\
B_{k,t-1} &= B_{k-1,t} \quad k \in K > 1 \\
X_{R_{k,t}} &= 0 \quad \forall t \in T \\
B_{k} &\leq B_{k-1,t} \quad k \in K < ML \\
CE_t, SE_t, S^+_t, \text{ and } S^-_t &> 0
\end{align*}
\]

The total usable energy stored in this model is summed up at 2.51 kWh, which requires 5.19 kWh of energy to store. For the purpose of optimization, household electricity consumption data was collected by the authors from a single household, connected to an off-grid solar photovoltaic plant. The plant, located at geographical coordinates 33.5, 73.1, has been sized with a 5 kVA inverter with 19 solar panels, each.

IV. COMPUTATIONAL RESULTS

In this section, simulation results and results from a sensitivity analysis on multiple problem sizes and planning horizons is presented. Then, the model effectiveness is measured in term of minimizing unmet demand and balancing energy supply. The application of the proposed model is investigated during 24 (a day) to 168-hour (a week) and the height of the tower is limited to 50 blocks. The assumed difference in stored energy versus released energy against the height of the tower is limited to 50 blocks. The assumed difference in stored energy versus released energy against the height of the tower is shown in Figure 7. The computational experiments for these data sets are completed using CPLEX solver embedded in GAMS 26.1 on a computer with Intel Core i5-8250U CPU @ 1.6GHz and 8GB of RAM. The simulation based computation model described earlier was run in Matlab 2019b ran on a machine with the exact same specifications as well. The amount of energy stored and released by this model is dependent on Equation 1, and is represented in Figure 10.

A. EXPERIMENTAL DESIGN

The total usable energy stored in this model is summed up at 2.51 kWh, which requires 5.19 kWh of energy to store. For the purpose of optimization, household electricity consumption data was collected by the authors from a single household, connected to an off-grid solar photovoltaic plant. The plant, located at geographical coordinates 33.5, 73.1, has been sized with a 5 kVA inverter with 19 solar panels, each.
TABLE 3. Energy wastage for different configurations.

| W  | L  | H  | I  | Total Energy Wasted / Wh |
|----|----|----|----|--------------------------|
| 5  | 5  | 50 | 20 | 77.4                     |
| 5  | 5  | 50 | 35 | 790.4                    |
| 10 | 10 | 50 | 10 | 97.7                     |
| 10 | 10 | 50 | 20 | 547.4                    |
| 10 | 10 | 50 | 35 | 934.9                    |
| 10 | 10 | 50 | 50 | 3822.8                   |

rated at 210 wp. The collected dataset does not include any alternate energy storage systems, and already accounts for the efficiencies of the system itself.

The consumption of the house has been scaled to equal the average production from the solar panels, during the month of June 2019 in order to calculate length of possible stand-alone supply from the proposed model, and is summarized in Table 3. There is a significant gap between supply and demand, for example, at hour 20, 1262 Wh of energy cannot be met by available solar supply. On the other hand, there are 1855 Wh of excess energy at hour 14. It is worthy to be mentioned that the total demand and supply is assumed to be at an equal value, (30kWh), and the total gap in 24h is zero.

B. UNOPTIMIZED SIMULATION RESULTS

A simulation of a 5 × 5 tower with a maximum allowable height of 50 blocks and an initial height of 20 blocks is shown in figure 9. This simulation yields a total of 77.4Wh of energy that is either not stored due to no available storage spaces, or oversupply of energy due to demand being slightly greater than available options for energy retrieval from the model as shown in figure 8 and summarized in table 4 for different configurations.

In scenarios with higher initial block heights, the simulation often resulted in the blocks being capped at their maximum allowable height (50 blocks) resulting in higher wasted energy. Overall, the system shows promise for models with 5×5 configurations and an initial starting height of 20 blocks. By the end of the day, the tower is almost empty as shown in figure 9. At the start of the next day, this requires some additional energy to restart. If the tower is not reset, it reaches zero blocks by hour 2 of the second day. A simulation of the 10×10 configuration with 20 blocks over a period of 168 time intervals (1 week) yields significant energy wastage over time. Furthermore, the tower empties by hour 23 of day 4.

C. OPTIMIZATION RESULTS

To manage the gap between supply and demand a VBESS approach is utilized. For this purpose, a plan for releasing and stacking blocks is required. For a case with 5 (w) × 5 (L) × 50 (H), I = 21, and TH = 24h the results are reported in Table 5. Due to a shortfall in energy supply between hours 1 and 6, the model tends to release blocks to supply energy. The model also ensures that the number of blocks in one level (Bkt) is always higher than the number of blocks in the level above it, thereby maintaining tower stability.

Results during daylight hours are presented in figure 10. The model tends to place blocks in the tower to store excess energy. In figure 11, the value of consumed energy to store blocks, CE, and released energy to compensate lake of energy supply, SE, are depicted. As can be concluded during daylight (hours 9 to 18), considerable amount of energy has been stored for use during the coming high-demand hours (hours 20 to 24).

The advantage of using this idea can be perceived by comparing unmet demand before and after using this concept, as illustrated in figure 12. As evident in this graph, there is a significant modification by utilizing the proposed VBESS model, such as lower unmet demand and greater excess supply in certain time periods.

In order to examine the model performance for a longer time period, it is run for a tower with 10 × 10 × 50 dimension, TH = 168h (one week), and I = 35. As illustrated in Figure 14, the same fluctuation for unmet demand and excess supply is observed, which rises to about 2000 Wh and drops down to around -2200 Wh. Using VBESS, max unmet demand observed in all time periods is 0 Wh. This is in contrast to running the simulation without the mathematical model where unmet demand is seen to mimic a scenario without the storage system after hour 121, as shown in figure 13.

D. ANALYSIS ON THE IMPACT OF INPUT PARAMETERS

In this section, the model performance is investigated by conducting a sensitivity analysis on input parameters. As shown
in table 4, dimensions of the tower (W, L, and H), $I$, and TH are the main input parameters of the model which are considered in this analysis. In all scenarios, due to the initial condition, supplied energy by the system ($SE_t$) is greater than consumed energy ($CE_t$). However, it should be noted that these large amounts of $CE_t$ show that this concept is working and uses considerable amount of excess supply to store and reduce maximum unmet demand in all investigated time periods. In addition, the objective function value in all examples corroborates the proposed model as a viable solution to decrease maximum unmet demand to zero from a high of 2200 Wh over one week.

Furthermore, the results in Table 6 show that to achieve zero unmet demand (objective function), value of $I$, full levels at the starting time, should be set to a proper amount. As depicted in figure 14, a sensitivity analysis on its value is performed and the results show that to get zero unmet demand for a tower with $10 \times 10 \times 50$ dimension in a week (168h), at least 22 full levels at the beginning of the planning horizon are needed.

### TABLE 5. Implementation results for VBESS with $5 \times 5 \times 50$ configuration, $I_0 = 21$ blocks over 24 hours.

| $B_{it}$ | $t$       |
|---------|----------|
|         | 1 2 3 4 5 |
| 1       | 25 25 25 25 25 |
| 2       | 25 25 25 25 25 |
| 3       | 25 25 25 10 10 |
| 4       | 25 25 13 10 9 9 |
| 5       | 25 20 13 10 8 8 |
| 6       | 25 15 12 10 8 8 |
| 7       | 25 15 12 10 8 7 |
| 8       | 25 14 12 10 8 7 |
| 9       | 25 14 12 10 8 6 |
| 10      | 25 14 12 10 8 6 |
| 11      | 25 14 12 10 8 6 |
| 12      | 25 14 12 10 8 6 |
| 13      | 25 14 12 10 8 6 |
| 14      | 25 14 12 10 8 6 |
| 15      | 25 14 12 10 8 6 |
| 16      | 25 14 12 10 8 6 |
| 17      | 25 13 12 10 8 6 |
| 18      | 25 13 11 9 7 6 |
| 19      | 25 13 11 9 7 6 |
| 20      | 25 13 11 9 7 4 |
| 21      | 25 13 11 9 7 3 |

| $X_{it}$ | $t$       |
|---------|----------|
|         | 1 2 3 4 5 |
| 1       | 0 0 0 0 0 |
| 2       | 0 0 0 0 0 21 |
| 3       | 0 0 15 0 0 6 |
| 4       | 0 12 3 1 0 5 |
| 5       | 5 7 3 2 0 4 |
| 6       | 10 3 2 2 0 4 |
| 7       | 10 3 2 2 1 3 |
| 8       | 11 2 2 2 1 3 |
| 9       | 11 2 2 2 2 2 |
| 10      | 11 2 2 2 2 2 |
| 11      | 11 2 2 2 2 2 |
| 12      | 11 2 2 2 2 2 |
| 13      | 11 2 2 2 2 2 |
| 14      | 11 2 2 2 2 2 |
| 15      | 11 2 2 2 2 2 |
| 16      | 11 2 2 2 2 2 |
| 17      | 12 1 2 2 2 2 |
| 18      | 12 2 2 2 1 2 |
| 19      | 12 2 2 2 1 2 |
| 20      | 12 2 2 2 3 0 |
| 21      | 12 2 2 2 4 3 |
E. IMPACT OF INTERMITTENCY IN ENERGY DEMAND AND SUPPLY

A further sensitivity analysis conducted for different levels of input parameters results in similar promising results. To incorporate stochasticity and intermittency of weather-influenced solar radiation data, the solar incidence data for Berlin was sampled over the entire year of 1999 [43], [44]. From this, the hourly consumption across 360 days was sampled to find the predicted electricity consumption mean and standard deviations for a solar system rated at 5.5kVA. This was utilized to create 1 million scenarios over a 7-day (168-hour) period. The variable nature of household consumption can be taken into account by way of simulating a typical household’s electricity consumption data using a load profile generator [45]. The demographic of the house in question is assumed multigenerational, with varying electricity consumption based on typical usage patterns discussed in literature and simulated over one year [44].

Of the two sets of yearlong simulations, over the 168 hour period the expected supply and demand are summarized as $E_S$ and $E_D$ respectively. The highest available (best) supply values and the lowest available (worst) supply values

| WXH | $THH$ | Optimal | $SUM$ | $SUM$ | $SE_t$ | $T_{MIN}$ |
|-----|-------|---------|-------|-------|--------|-----------|
| I   |       | $CE_t$  | $kWh$ | $kWh$ |        |           |
| 5   | 20    | 24      | 0     | 9.1   | 15.3   | 0.1       |
| 5   | 35    | 48      | 0     | 11.7  | 33.8   | 0.2       |
| 5   | 35    | 72      | 0     | 32.8  | 49.1   | 2.2       |
| 10  | 10    | 24      | 0     | 9.0   | 16.0   | 0.0       |
| 10  | 10    | 48      | 26    | 28.4  | 29.3   | 20.0      |
| 10  | 10    | 72      | 110   | 43.8  | 40.3   | 41.2      |
| 10  | 20    | 48      | 0     | 4.2   | 38.2   | 0.5       |
| 10  | 20    | 72      | 0     | 20.1  | 49.6   | 0.8       |
| 10  | 20    | 168     | 9     | 102.4 | 106.9  | 52.8      |
| 10  | 35    | 72      | 0     | 9.7   | 91.9   | 0.4       |
| 10  | 35    | 168     | 0     | 40.8  | 133.2  | 0.9       |
| 10  | 50    | 168     | 0     | 32.2  | 144.1  | 3.7       |
are summarized as $B_S$ and $W_S$ respectively. The highest demand consumption (worst) and the lowest demand consumption (best) are summarized as $W_D$ and $B_D$ respectively. The values are shown in figure 15. These cases are interlinked and the 9 overall scenarios have been simulated with the results summarized in table 7.

Table 7 shows that in the case of high (best) or expected supply values matching up against expected and low (best) demand, the optimization function minimizes unmet demand to zero. In cases where supply is low (worst), unmet energy demand ranges between 2.1 and 10.1 kWh depending on demand values. These optimization runs included a tower of dimensions $10 \times 10 \times 35$, completely full in the initial condition. In case of low (worst) supply and high (worst) demand, the unmet demand is optimized to a minimum of 228 kWh over a 7-day period. This stochastic dataset shows great variability and in the $W_S - W_D$ scenario, the total consumed energy $CE_t$ is 35kWh against a total observed energy demand of 168kWh and supply of 84 kWh.

V. CONCLUSION

Taking into account the potential of reducing the gap between energy demand and supply using an energy storage system, this paper proposes a control strategy for a novel energy storage system using blocks to store energy and release it to produce energy when necessary. This ESS is easier to implement than other comparable ancillary energy storage methods which are severely restricted by their need for suitable geography and morphology of terrain. It is competently priced in monetary and complexity based terms, and gives comparable or better overall system efficiency than some storage methods such as CAES and PHS due to simpler construction and the lack of self-discharge related issues. A mathematical model is presented in this paper which aims to minimize the maximum unmet demand in all time periods. Real-world data is adopted from consumption of a house that has been scaled to equal the average production from the solar panels, during the month of June 2019. The computational results show that the above-mentioned ESS’s performance has the potential to bring significant improvement in reducing unmet demand. In all data sets, the proposed system is effective and the ultimate goal, elimination of unmet demand, has been met. Even when accounting for the intermittency of both energy supply and demand, the results show significant potential as an energy storage mechanism. The mathematical model shows approximately 30% longer energy storage while minimizing unmet energy demand in the deterministic stage. When accounting for worst case scenarios, the model is able
to increase availability of energy by storing some of the available 84 kWh over 7 days to account for the 1291 kWh demand.

The mathematical model highlights the potential for reducing wasted energy when compared to the un-optimized model by optimizing block placement and removal in the temporal domain. This results in the blocks lasting longer due to essentially no wasted energy, as is the case between the one-week scenarios highlighted in figure 13. The mathematical model shows that for a week planning horizon, this storage system is able to shift blocks stored in a tower of initial height 22 blocks to avoid unmet demand completely, which used to be 2231Wh. The model suggests that such a system can be used to distribute the peak energy generation by a photovoltaic system, kept between 85W and 1900W for a total of 30kWh per day, to allow for energy supply during high demand periods. The system cannot be compared to traditional lithium ion batteries, due to their higher efficiency and lower overall installation size and complexity, but can be compared to an ancillary level storage method such as pumped hydro storage. VBESS allows for converting existing compressed landfill sites into a long term energy storage method, and may show promise in larger installations due to lower cost to scale up and more efficient crane and generator installations.

VI. FUTURE WORKS

For the future research, implementation the mathematical model for a longer term period, such as one year, and finding the best size for the tower are recommended. Furthermore, future works on this model should involve the use of robust optimization to optimize multiple such towers for a larger supply-demand configuration. Due to the optimization model complexity, solving the mathematical model for long time periods is time consuming. This is why a heuristic or meta-heuristic solution approach is also required and it is an open research field. It might also be imperative to model the system based on load profiles for a larger set of consumers and photovoltaic installations. In such cases, key variables to study would include the difference between this proposed model and an hourly supply and demand matching algorithm. By optimizing for hourly unmet demand over longer periods of time, the mathematical model should be able to make the blocks placed in the initial condition last longer than the latter. Further studies can incorporate other onsite generation facilities such as wind turbines. A more complicated model taking into account inherent inefficiencies such as the speed of motor and generator rotation coupled with braking distances needs to also be examined. Such a model would also look at the spatial displacement as a minimization factor due to the energy required to reach a block while moving at a constant altitude.

ACKNOWLEDGMENT

(Sajjad Haider and Hani Shahmoradi-Moghadam contributed equally to this work.)

REFERENCES

[1] E. Bomppard, Y. Ma, R. Napoli, and G. Abrate, “The demand elasticity impacts on the strategic bidding behavior of the electricity producers,” IEEE Trans. Power Syst., vol. 22, no. 1, pp. 188–197, Feb. 2007.

[2] Y. Ma, J. Ji, and X. Tang, “Triple-objective optimal sizing based on dynamic strategy for an Islanded hybrid energy microgrid,” Int. J. Green Energy, vol. 14, no. 3, pp. 310–316, Feb. 2017.

[3] F. Bournanci, S. Rahnamayan, and G. F. Naterer, “Optimal design methods for hybrid renewable energy systems,” Int. J. Green Energy, vol. 12, no. 2, pp. 148–159, Feb. 2015.

[4] M. H. Roos, D. A. M. Geldmeijer, H. P. Nguyen, J. Morren, and J. G. S lootweg, “Optimizing the technical and economic value of energy storage systems in LV networks for DNO applications,” Sustain. Energy, Grids Netw., vol. 16, pp. 207–216, Dec. 2018.

[5] J. P. Barton and D. G. Infield, “Energy storage and its use with intermittent renewable energy,” IEEE Trans. Energy Convers., vol. 19, no. 2, pp. 441–448, Jun. 2004.

[6] J. P. Deane, B. P. O Gallachóir, and E. J. McKeogh, “Techno-economic review of existing and new pumped hydro energy storage plant,” Renew. Sustain. Energy Rev., vol. 14, no. 4, pp. 1293–1302, May 2010.

[7] S. Pazouki, M.-R. Haghifam, and J. Olamaei, “Short term scheduling of multi carrier systems through interruptible load and energy storage toward future sustainable energy needs,” in Proc. 5th Int. Conf. Electr. Electron. Eng. (ELECO), Nov. 2013, pp. 77–81.

[8] R. Hebner, J. Beno, and A. Walls, “Flywheel batteries come around again,” IEEE Spectr., vol. 39, no. 4, pp. 46–51, Apr. 2002.

[9] S. Kooi-Hayeegh and M. A. Rosen, “A review of energy storage types, applications and recent developments,” J. Energy Storage, vol. 27, Feb. 2020, Art. no. 101047.

[10] T. M. I. Mahlia, T. J. Saktisahadan, A. Jannifar, M. H. Hasan, and H. S. C. Matseelar, “A review of available methods and development on energy storage; Technology update,” Renew. Sustain. Energy Rev., vol. 33, pp. 532–545, May 2014.

[11] M. Aneke and M. Wang, “Energy storage technologies and real life applications—A state of the art review,” Appl. Energy, vol. 179, pp. 350–377, Oct. 2016.

[12] D. Wang, R. Wu, X. Li, C. S. Lai, X. Wu, J. Wei, Y. Xu, W. Wu, and L. L. Lai, “Two-stage optimal scheduling of air conditioning resources with high photovoltaic penetrations,” J. Cleaner Prod., vol. 241, Dec. 2019, Art. no. 118407.

[13] R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala, and I. Gyuk, “Energy management and optimization methods for grid energy storage systems,” IEEE Access, vol. 6, pp. 13231–13260, 2018.

[14] R. Li, W. Wang, and M. Xia, “Cooperative planning of active distribution system with renewable energy sources and energy storage systems,” IEEE Access, vol. 6, pp. 5916–5926, 2018.

[15] G. J. May, A. Davidson, and B. Monahov, “Lead batteries for utility energy storage: A review,” J. Energy Storage, vol. 15, pp. 145–157, Feb. 2018.

[16] S. J. Lancashire, “Life-cycle comparison of different battery types for use with photovoltaic systems,” in Proc. Conf. Rec. 20th IEEE Photovoltaic Specialists Conf., Sep. 1988, pp. 1157–1163.

[17] D. J. Swider, “Compressed air energy storage in an electricity system with significant wind power generation,” IEEE Trans. Energy Convers., vol. 22, no. 1, pp. 95–102, Mar. 2007.

[18] D. Zhang, Z. Li, J. Zhou, and K. Wu, “Development of thermal energy storage concrete,” Cement Concrete Res., vol. 34, no. 6, pp. 927–934, 2004.

[19] C. F. Jenkins, “Gravity-railway device,” U.S. Patent 1216694 A, Feb. 20, 1917. [Online]. Available: https://patents.google.com/patent/ US1216694.

[20] C. Bueno and J. A. Carta, “Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary islands,” Renew. Sustain. Energy Rev., vol. 10, no. 4, pp. 312–340, Aug. 2006.

[21] T. Ma, H. Yang, L. Lu, and J. Peng, “Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong,” Renew. Energy, vol. 69, pp. 7–15, Sep. 2014.

[22] T. Brijs, A. van Stiphout, S. Siddiqui, and R. Belmans, “Evaluating the role of electricity storage by considering short-term operation in long-term planning,” Sustain. Energy, Grids Netw., vol. 10, pp. 104–117, Jun. 2017.

[23] M. Faisal, M. A. Hannan, P. J. Ker, A. Hussain, M. B. Mansor, and F. Blaabjerg, “Review of energy storage system technologies in microgrid applications: Issues and challenges,” IEEE Access, vol. 6, pp. 35143–35164, 2018.
[24] A. Berrada, K. Loutfi, and R. Garde, “Dynamic modeling of gravity energy storage coupled with a PV energy plant,” Energy, vol. 134, pp. 323–335, Sep. 2017.

[25] T. Mostyn, M. Chilcott, and M. D. McCulloch, “Gravity energy storage with suspended weights for abandoned mine shafts,” Appl. Energy, vol. 239, pp. 201–206, Apr. 2019.

[26] W. R. Peirzke and M. Brown, “Utility scale electric energy storage system,” U.S. Patent 8,593,012 B2, Feb. 10, 2013. [Online]. Available: https://patentimages.storage.googleapis.com/8/6/3/54/12d833932a887e_US8952563.pdf

[27] W. R. Peirzke and M. Brown, “Rail based potential energy storage for utility grid ancillary services,” U.S. Patent 8,023,025 B4, Apr. 18, 2014.

[28] A. Fyke, “The fall and rise of gravity storage technologies,” Joule, vol. 3, no. 3, pp. 625–630, 2019.

[29] V. B. Venkateswaran, D. K. Saini, and M. Sharma, “Environmental constrained optimal hybrid energy storage system planning for an indian distribution network,” IEEE Access, vol. 8, pp. 97793–97808, 2020.

[30] M. H. Amrollahi and S. M. T. Bathae, “Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone micro-grid subjected to demand response,” Appl. Energy, vol. 202, pp. 66–77, Sep. 2017.

[31] A. Eshraghi, G. Salehi, S. Heibati, and K. Lari, “An enhanced operation model for energy storage system of a typical combined cool, heat and power based on demand response program: The application of mixed integer linear programming,” Building Services Eng. Res. Technol., vol. 40, no. 1, pp. 47–74, Jan. 2019.

[32] D. Liu, C. Shang, and H. Cheng, “A two-stage robust optimization for coordinated planning of generation and energy storage systems,” Proc. IEEE Conf. Energy Internet Energy Syst. Integr. (EI2), Nov. 2017, pp. 1–5.

[33] B. Lokeshputra and S. Sivasubramani, “Multi-objective home energy management with battery energy storage systems,” Sustain. Cities Soc., vol. 47, May 2019, Art. no. 101458.

[34] J. D. Hunt, B. Zakeri, G. Falchetta, A. Nascimento, Y. Wada, and K. Riahi, “Mountain gravity energy storage: A new solution for closing the gap between existing short- and long-term storage technologies,” Energy, vol. 190, Jan. 2020, Art. no. 116419.

[35] (2020). Energy Vault. Accessed: Feb. 9, 2020. [Online]. Available: https://energyvault.com/

[36] Volume-to-Weight Conversion Factors, U. S. Environmental Protection Agency, Epa, Washington, DC, USA, 2016.

[37] Determining Electric Motor Load and Efficiency, U.S. Dept. Energy, Mot. Challenge, Washington, DC, USA, 2013.

[38] S. Van Sterkenburg, E. Rietveld, F. Rieck, B. Veenhuizen, and H. Bosma, “Analysis of regenerative braking efficiency—A case study of two electric vehicles operating in the rotterdam area,” in Proc. IEEE Vehicle Power Propuls. Conf., Sep. 2011, pp. 1–6.

[39] D. Hog, Costs for Municipal Waste Management in the EU Final Report to Directive General Environment, Brussels, Belgium: European Commission, 2001.

[40] M. Mozazimi, J. Moradi, H. Shahinzadeh, G. B. Gharehpetian, and H. Mogool, “Optimal economic operation of microgrids integrating wind farms and advanced rail energy storage system,” Int. J. Renew. Energy Res., vol. 8, pp. 1155–1164, Jun. 2018.

[41] J. Dhillon, A. Kumar, and S. K. Singal, “A stochastic approach for the operation of a wind and pumped storage plant under a deregulated environment,” Int. J. Green Energy, vol. 13, no. 1, pp. 55–62, Jan. 2016.

[42] C. D. Botha and M. J. Kamper, “Capability study of dry gravity energy storage,” J. Energy Storage, vol. 23, pp. 159–174, Jun. 2019.

[43] NASA. (2019). Power Project. NASA Langley Research Center (LaRC) POWER Project. Accessed: Jan. 20, 2020. [Online]. Available: https://power.larc.nasa.gov/

[44] S. Haider and P. Schegner, “Data for heuristic optimization of electric Vehicles’ charging configuration based on loading parameters,” Data, vol. 5, no. 4, p. 102, Oct. 2020.

[45] N. Plüggradt and U. Munzweyer, “Synthesizing residential load profiles using behavior simulation,” Energy Procedia, vol. 122, pp. 655–660, Sep. 2017.

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