Storing the Sun

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Summary

When living off-the-grid, an efficient energy storage system is the most important thing to be considered. With the multitude of solar power batteries on the market, choosing the one that fits a household's needs can be a challenge. The differences in what a person seeks from their battery-operated home and how much they want to rely on a battery in their everyday life are some factors that can make this especially difficult. Maintenance, cost, battery efficiency, and durability also come into play while making an innovatively designed model.

We started to develop a model by first organizing the data that we had and examining additional battery samples. After making a list of our assumptions, we noticed the many factors that had to be taken into account, which directed our focus to models that would allow us to consider many factors at once. One such model was a decision matrix where a list of specific criteria is used to analyze the different batteries. Our decision matrix consisted of 10 weighted criteria. Each criterion received a weight from 1-10, with 1 being of little importance and 10 being most important. We assessed how well each battery fit our established criteria from 0-5, with 0 being does not meet criteria at all and 5 being meets/exceeds criteria. From there, the batteries were scored using the weighting and ranking system, and the highest score determined which product the homeowner should choose. Our first model focused on the average single-family home in the United States, and we found that the Discover AES 7.4 kWh would be the best fit.

Our next model allows the homeowner to express their personal needs and have a straightforward result. Based on the homeowner's requirements, including the cost, the efficiency, or the ability to operate individually, the battery choice is customizable. Rather than our first model's chosen criteria weighting, the criteria in this generalized model are weighted based on the importance as determined by the homeowner.

A look to the future brings us to building materials that can support many functions, from structural health monitoring to energy storage. Cement batteries could be used as an alternative to commercially available batteries, however, they have low energy outputs. It has been proposed that solar panels can be coupled with cement batteries to create rechargeable batteries. While there is little research on rechargeable cement batteries, their development can not only help address the energy crisis but also provide a more sustainable option for energy storage.

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The Problem

Problem Restatement

A 1600 square-foot home is being built in a remote area. This house will utilize solar power to provide electricity for its inhabitants. Solar power is an environmentally-friendly renewable energy source, converting energy from the sun into electrical energy. While the sun can provide a consistent source of energy during a sunny day, users of solar power must consider supporting the energy requirements at night or on a cloudy day. Pulling energy from the grid is one option for the times when solar panels are not producing enough energy. Another option is to go off-the-grid, demanding constant electricity independence. Due to the remote living situation, connecting to the grid has a very high cost, so it is important to minimize the cost of energy storage while maximizing the amount of energy it can store.

Energy storage systems allow energy (including solar energy) to be captured and stored to use when needed. Most solar homes that use energy storage systems use a type of battery. The specifications and costs of batteries on the market vary drastically. Additionally, some homeowners have a large single battery, while others may have a “bank”, or system of two or more batteries. Each homeowner should consider an energy storage system that is appropriate for their situation.

Our team was tasked with considering various criteria to determine the most appropriate energy storage system for solar power users and owners of a 1600 square-foot home in a remote area.

Background and Research

Energy Use & Appliances

An average U.S. household is expected to consume about 11,000 kWh of electricity annually (*Electricity use in homes*, 2019). For small homes (approximately 1600 square feet), this energy is typically divided into approximately 13 different rooms, each with different appliances and electronics (Emrath, 2013). Major home appliances include refrigerators, freezers, clothes washers/dryers, stoves, ovens, and dishwashers (Schwartz et al., 2017). Modern comforts, like air conditioning and heating systems, can also be found in households, though styles vary (i.e. central air conditioning vs. window air conditioner units). Lighting fixtures and security systems are also common elements found in nearly every household. Other miscellaneous devices and appliances include cell phones, computers, laptops, microwaves, and small appliances (such as hair-dryers, irons, vacuums, etc.).

Battery Qualities

Various qualities must be considered to compare and determine which system would be best suited for our situation.

Two types of power ratings, the continuous power rating and the instantaneous power rating, can be used to help us assess the battery options. Continuous power ratings show the amount of power that a battery can supply continuously, while instantaneous power ratings show the amount of power that a battery can provide in short bursts, but cannot sustain continuously. In short, a high continuous power rating is ideal for powering more of the home at once and a high instantaneous power rating is ideal for powering more energy-intensive appliances. We found that not all batteries had available information about both of these ratings.

Other qualities we must include in our consideration are the usable capacity and the round-trip efficiency. Usable capacity is the actual energy that is available for consumption (*Battery Storage: What do you need to know?*, 2017). This is important for running a home for a longer amount of time. The round-trip efficiency is the percentage of the energy that a user will get out of the battery for the amount that was put into it.

Additionally, different types of batteries have different properties. The main types include lead-acid and lithium-ion batteries. They are both considered ideal for full-time, off-grid living. Lead-acid batteries are known for their reliability and low prices, however, they tend to require higher maintenance and have lower safety ratings than lithium-ion batteries. While lithium-ion batteries can provide the longest lifetime, they are more expensive and are newer to the market.

An important aspect of our models was that most houses off the grid are 12 volts, 24 volts, or 48 volts. A 12-volt house would need a few batteries and would be able to run things such as general lighting, small appliances, and any appliances that don't generate heat. A 24-volt house is considered standard for an off-grid settlement and would require a bank of batteries or one large battery. These houses can support bigger appliances such as washing and drying machines, refrigerators, and any appliances that generate heat. A 48-volt house can support the same big appliances as well as commercial use items, but for much longer and with more power (Hosfeld, 2020).

Our team was originally given five batteries used for solar storage to consider. These batteries included the Deka Solar 8GCC2 6V 198, Trojan L-16 -SPRE 6V 415, Discover AES 7.4 kWh, Electriq PowerPod 2, and the Tesla Powerwall+[1]. Additionally, we found the Battle Born Battery, VMAX SLR50 50ah, SimpliPhi Power PHI 3.8-M, and the KiloVault 12V Advanced Sealed Battery[1]. We chose these as they had a range of different prices, specifications, and representations of lithium-ion and lead-acid battery types.

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[1] We have chosen to abbreviate each of the battery names for the rest of the paper. Deka (Deka Solar 8GCC2 6V 198), Trojan (Trojan L-16 -SPRE 6V 415), Discover (Discover AES 7.4 kWh), Electriq (Electriq PowerPod 2), Tesla (Tesla Powerwall+), Battle Born (Battle Born Battery), VMAX (VMAX SLR50 50ah), SimpliPhi (SimpliPhi Power PHI 3.8-M), and the KiloVault (KiloVault 12V Advanced Sealed Battery).

Batteries	Cost	Type[2]	Voltage	Usable Capacity	Continous power rate	Instantaneous Power Rate	Round Trip Efficiency	Predicted Lifespan	Cost per year
	($)		(v)	(kWh)	(kWh)	(kw/s)	(%)	years	($)
Deka	368.0	SGLA	6	1.18	0.00245	[3]	80-85	5.0	73.60
Trojan	492.0	FLA	6	2.50	0.19000	[3]	80-85	4.5	109.33
Discover	6478.0	LFP	48	7.40	6.65000	4.80	>95	8.0	809.75
Electriq	13000.0	LFP	100	10.00	7.60000	0.15	96.6	10.0	1300.00
Tesla	8500.0	NMC	350	13.50	7.00000	1.00	90	10.0	850.00
Battle Born	950.0	LFP	12	1.15	1.20000	0.80	97	13.0	73.08
VMAX	170.0	AGM	12	0.45	0.60000	0.00	80	9.0	18.89
SimpliPhi	2694.6	LFP	24	2.13	1.80000	0.03	98	10.0	269.46
KiloVault	517.3	AGM	12	1.11	6.00000	1.68	80-90	5.0	103.46

Table 1: Data and specifications for batteries.

[2] Battery type was abbreviated throughout this paper for the sake of conciseness. SGLA stands for Sealed Gel Lead Acid, FLA stands for Flooded Lead Acid, LFP stands for Lithium Iron Phosphate ($LiFePO_4$) (a type of lithium-ion), NMC stands for Lithium Nickel Manganese Cobalt Oxide, AGM stands for Absorbent Glass Mat.
[3] No information available.

Assumptions

Assumption	**Justification**
The house is exposed to an average of 12 hours of sunlight per day.	Because this off-the-grid house relies on solar power, we feel it is important to assume that they do not live in a place near the poles where they do not receive sunlight during certain seasons.
There are 3 people in the household.	The average household size in the USA is about 3.15 people (*Average family size in the US 1960-2018*, 2018).
The house is a single-family detached house.	Since the requirements for the problem are to look at a 1600 sq ft. house in a remote area, we did not look at apartment buildings or multi-family houses.
The homeowners will go off-the-grid during a typical year (i.e. not during a pandemic or lockdown).	The COVID-19 pandemic created restrictions on leaving the home and demanded an increase in electrical usage. Therefore, we decided to assume the family would go off-the-grid around the present time, or even sometime in the future.
The house is located in the United States of America (U.S.).	Most batteries we used were marketed by U.S. companies. Other battery companies were located in North America, so we thought it would be fair to approximate the location of this house to the U.S.
Different brands and/or types of batteries cannot be combined in series or parallel.	Many companies stated that it was not advised to attach different types of batteries together due to the possibility of explosion or chemical release. Even if adding different types of batteries could make one powerful battery, the safety risk would be too great.
Lifespans of batteries are based on warranties, if not detailed in company specification sheets.	Although most batteries did provide an expected lifespan, some didn't. The batteries that did not provide lifespans did include warranties, so we assumed that a battery's lifespan would be greater than or equal to the length of the warranty.

Table 2: The assumptions we made and justification.

Strategy

As we started to attack the problem, we came up with a couple of questions to guide us through our research and model building. We tried to answer the questions based on our assumptions and research to better understand the house we would be powering.

Q. How many people will be using energy in this home?

A. Three people live in the house.

Q. What items in the home will need energy and how much energy will they need?

A. An average U.S. household is expected to consume approximately 11,000 kWh in a year and 30.14 kWh in a day (*Electricity use in homes*, 2019). Major items in the home that require energy include a refrigerator, heating system, AC system, washing and drying machines, a TV, and others (Schwartz et al., 2017).

Q. When will people in the home use energy?

A. Early in the morning and later at night, as adults generally have a 9-5 workday, and children are in school for about the same time frame. However, there are also devices and appliances that require constant energy.

Q. How many rooms are in the house?

A. Following a general house structure, there are thirteen rooms in the house (Emrath, 2013).

Q. What appliances are still running when they are not in active use/during the night?

A. Refrigerators and air conditioning/heating are usually still running during the night or when homeowners are not home.

Our second step was to develop a model that could recommend the best battery for the general public and one that could tailor to specific needs. We wanted something that addresses multiple criteria and something that deals with the data table we developed with our research. A couple of options stood out to us: flow chart, Java algorithm, and decision matrix. The Java algorithm was eliminated quickly due to potential complications in the code as well as our desire to create a simple and interpretable model. Ultimately, we decided to use a decision matrix for our first (specific) model, and a flow chart for our second (generalized) model.

We also decided to add batteries that were not included in the given sample to provide a wider range of items that could be tested. Different websites were used to find an additional 4 lead-acid or LFP batteries.

The Model

Specific Model

Our first model is a decision matrix or a chart that takes into consideration different criteria and the importance of each criterion. The weighting of the criterion was based on what we thought the average family in America would need and considered our questions and answers described above. Each criterion received a weight from 1-10, with 1 being of little importance and 10 being most important. We scored each battery from 0-5 for each criterion, 0 being they did not meet the criterion and 5 being they met/exceeded the criterion. The rating for each battery was based on our data in Table 3. The rating for each battery's ability to meet the criterion was multiplied by the criterion's weighting. For each battery, the products previously described for each criterion were added up. The battery with the highest score is the one that fits the criteria best. The criteria chosen are:

- Criterion 1: Round-trip efficiency is greater than or equal to 90%.
  - A very high round-trip efficiency is ideal for maximizing the amount of energy used from the energy collected.
- Criterion 2: Usable capacity is higher than 7 kWh.
  - A high usable capacity is ideal for running the home for a longer amount of time.
- Criterion 3:The cost per year (long-term cost) is "good."
  - This criterion was made to weed out batteries that our defined homeowners could not afford. To evaluate this, we found the ratio of price to expected lifespan.
- Criterion 4: Long lifespan (longer than 5 years).
  - An off-the-grid homeowner would desire a longer battery lifespan so they do not have to frequently replace their batteries.
- Criterion 5: Maintenance should not exceed the original cost.
  - Costly maintenance may create future hazards or unplanned financial burdens.
- Criterion 6: LFP battery.
  - LFP batteries are considered the safest batteries. They also have the longest lifetimes and require no maintenance.
- Criterion 7: Can support a 24 v or 48 v household in series.
  - Batteries that can work in both series and in parallel are ideal for an off-the-grid house, as it is easy for the homeowners to add/subtract batteries as electrical needs change.
- Criterion 8: Can support a 24 v or 48 v household by itself.

    - Although batteries in series/parallel would be ideal, some people may not have space in their house or the time to upkeep a bank of batteries, in which case we wanted to find a singular battery for them to use.
- Criterion 9: Can support appliances that need continuous power.
    - Many major appliances require continuous power and this question allows us to narrow down the battery that can best support them based on its continuous power rating.
- Criterion 10: Can support appliances that need instantaneous power.
    - Some appliances require only short bursts of power. This question allows us to narrow down the battery that can best support them based on its instantaneous power rating.

Criteria	Weight	Deka	Trojan	Discover	Electriq	Tesla	Battle Born	SimpliPhi	VMAX	KiloVault
Round-trip efficiency should be greater than or equal to 90%	8	0	0	5	5	4	5	5	[4]	3
Usable capacity has to be higher than 7 kWh	10	0	4	5	5	4	0	[4]	[4]	[4]
Long-term cost: Cost-per year is "good"	9	3	1	4	2.5	3.5	5	4.5	4.75	3
Long lifespan (ideally longer than 5 years)	6	3	0	5	5	5	5	5	5	3
Maintenance should not exceed the original cost	4	3	2	5	5	5	5	5	5	5
LFP battery	1	0	0	5	5	0	5	5	5	0
Can support a 24 or 48 v household in series	6	5	5	3	0	0	5	5	5	5
Can support a 24 or 48 v household by itself	5	0	0	5	5	5	0	0	0	0
Can support appliances that need continuous power	8	2	2	3	5	4	2	2	2	4
Can support appliances that need instantaneous power	7	0	0	5	2	3	1	1	0	2
Total		87	87	224	192.5	178.5	170	165.5	127.75	119

Table 3: Model # 1 that determines the best battery for the average U.S. household.

[4] No information was available, therefore we could not rank these. Due to the companies' lack of accessible information, these received as rating of 0 in the respective criteria.

The Generalized Model

The generalized model was based on the decision matrix used in the previous model using the same criteria, with the exception of criterion 6. The model determined the criteria's weight by setting the decision matrix criteria as questions for the customer to rate based on what they perceived as important. We kept our predetermined ratings for the batteries from our first mode. The homeowner's customizable criteria weightings and our battery ratings would be multiplied and added in the same fashion as described in our specific model.

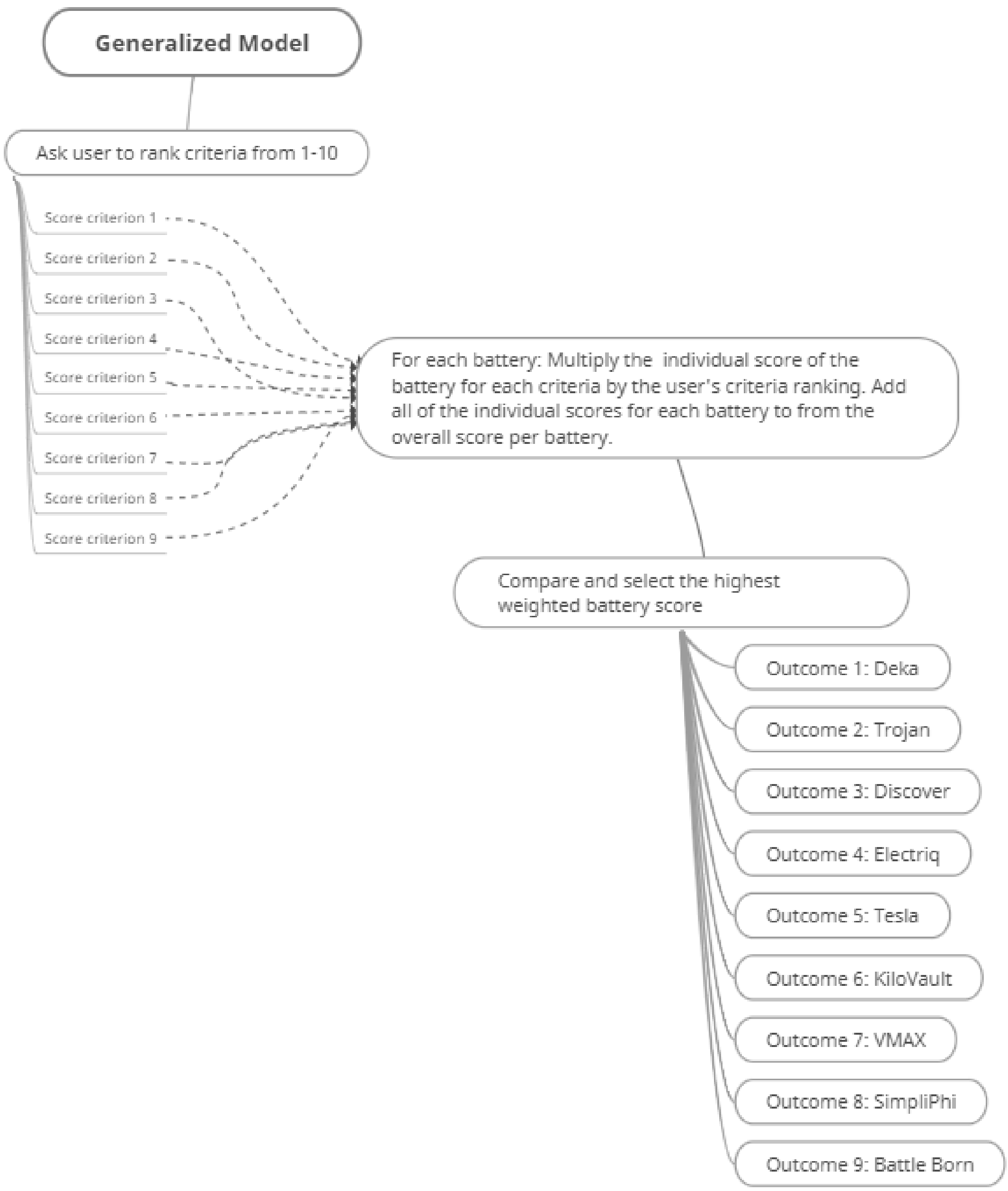

Fig. 1: A mind map of how the flow chart is structured.

Results

The Specific Model

For the specific model, we found that the Discover AES 7.4 kWh battery fit the criteria the best as it had the highest score. This LFP battery would be a good fit for an average family's needs due to its low maintenance, reasonable cost, high energy rates, and long lifetime.

The Generalized Model

For the generalized model, all of the battery types are possible outputs since the questioning process allows the customers to determine the weighting system. However, we did notice a trend in which batteries were more prevalent outcomes. The Discover AES 7.4 kWh, Electriq PowerPod 2, Tesla Powerwall+ showed up more times when testing different possible responses from homeowners. This is likely due to their ratings and scores being much higher than the other batteries. When Deka Solar 8GCC2 6V 198 and Trojan L-16 -SPRE 6V 415 were recommended to the customer, we decided to include the statement that the batteries should be used in a bank due to the energy outputs and battery capacity being too low to power a house when the battery was used on its own.

Model Analysis and Conclusions

Many people who desire to live off-the-grid may be intimidated by the sheer variety of batteries available. Our model provides a simple structure to lead their research efforts and guide them through the process of choosing a battery. Although our specific decision matrix has fixed values for the weighting, this is easily addressed and adjusted, as seen in our generalized flow-chart model. In the end, both of our models provide a simple and easily understood method to choose a battery to fit one's needs.

Strengths

- It is able to adapt to fit individuals' needs and wants.
- It is able to pinpoint why a certain battery has a lower score than others.
- Due to the models being weighted, all of the batteries have a chance of being chosen.
- The battery ratings for each criterion are based on data and company specifications.

Weaknesses

- The ratings for each criterion were based on data but subjectively chosen.

- When searching for batteries, not all of the needed information for each criterion could be found.
- It does not take the dimensions and weight of each battery into consideration.
- There may be some incorrect classifications of appliances as instantaneous or continuous.
  - The line between those two types of energies can be blurred, especially when census or questionnaire data combine appliance types.
- We only looked at a small sample of commercially available batteries— there are many others that we did not look at or rate.

Cementing the Future

Building materials, such as cement, have the potential to perform additional functions including storing energy. Cement provides structure and is the most used construction material in the world. If cement is able to store energy in a similar fashion to a battery, it can help address the energy crisis by providing a large amount of energy storage in a multipurpose structure. The research on cement batteries is extremely limited and the performance of the batteries is very poor. Additionally, prior to Zhang et al.'s study in 2021, there had not been any investigations on rechargeable cement batteries.

Should these cement batteries be applied to solar power storage, there are many advantages and disadvantages. Cement batteries can provide a large amount of energy storage due to the large volumes of cement-based structures. So, even if the energy per unit volume is not high, the capacity of the energy storage can be high. However, the energy outputs of previously tested cement-based batteries were very low. The energy density of the cement batteries was also found to be markedly lower than non-cement commercially available batteries.

Concrete foundations and basements are the most common in houses (*How to Build a Foundation*, n.d.). In any home—on- or off-the-grid—if the power ratings, usable capacity, round-trip efficiency, and costs of the rechargeable cement batteries are the same or comparable to the commercial battery required or the power used from the grid, these cement batteries can be a viable alternative. Before we can model and compare the use of cement batteries to currently available batteries for solar power storage, we must first determine how much cement is in an average 1600 square foot home and if all of this cement could be used for a cement battery. We would need this information to determine how much energy could be stored and the potential energy output. In terms of lifestyle and cost, we would need to determine the costs of purchasing, installation, and maintenance.

While the potential use of rechargeable cement batteries provides hope for addressing the energy crisis and environmental energy concerns, more research and development are needed before they can be applied to homes.

No Grid, No Problem

You have finally had enough. You're sick of your neighbors, the city is too loud, you've just gone through a big breakup. Whatever the reason is, you have decided that you need to move to a remote area.

As an environmentally conscious individual, you know that solar power is the best option for both your home and slowing the climate crisis. Due to your remote situation and the high costs of pulling energy from the grid, you have decided to go off-the-grid and invest in your own energy storage. Most solar-powered homes use batteries for energy storage. But what kind of energy storage system should you use?

There are many things to consider: battery efficiency, cost, battery lifetime, maintenance, energy needed, and how many batteries you can accommodate.

A weighting system, taking all of the listed points into consideration, can be used to aid in your decision-making process. In order to keep your home running and save the most money, you will likely prioritize costs, battery efficiency, and the amount of energy that is needed.

Your weighting system can be completely customizable in a few easy steps:

1. Decide what battery aspects are important to you. Are you looking for the lowest long-term cost? A battery that lasts the longest? Requires no maintenance? There is no limit to what you value!
2. Weight each of these aspects. Obviously, these are all important to you, but which ones are the most important? Assign them values from 1-10, with 1 being of little importance and 10 being the most important.
3. Figure out what battery options you have. This may seem intimidating, but Google and a few key search words can be your best friend. To start, try looking for "solar energy storage batteries for [criteria]." A few battery options that you can look at include Electriq PowerPod 2, Tesla Powerwall+, and Battle Born Battery.
4. Using your determined criteria (what you look for in a battery), you can rate each of the batteries' qualities from 0-5, with 0 being does not meet criteria at all and 5 being meets/exceeds criteria. Multiply your weightings by each rating and add up each of these to find a total for each battery.
5. Compare these totals and the highest is the one that's right for you!

In the future, cement batteries could be another option for solar energy storage. Since most buildings and homes have foundations of cement, it makes sense that researchers would want to find a way to optimize its abilities. Cement batteries can provide a large amount of energy storage due to the volume of cement in a typical building, though the energy output is comparably less than current commercially available batteries. Don't be overwhelmed though! While the potential use of rechargeable cement batteries provides promising hopes for addressing energy crisis and environmental energy concerns, more research and development are needed before they can be applied to homes.

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