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Summary Sheet

Shedding Light on a Battery of Batteries

On a never-ending quest to find the ultimate energy source, humanity inevitably stumbled upon renewable energy sources such as solar and wind energy, resulting in the construction of massive wind farms and solar power plants. The capability of harnessing such sources, apart from providing the world with essential energy, has allowed the dream of building a home capable of covering its own energy needs to materialize. Yet, the energy generated must be stored as the renewable sources are unstable.

The team is tasked with developing a model to choose the best battery, the most common energy storage device for contemporary applications, for an entirely-solar-powered home. To begin with, several assumptions, on which the team's models will be based on, are listed and justified to simplify the modeling process. The entire modeling process is separated into two parts: building a preliminary model designed to choose batteries for a remote, off-the-grid 1600-square-foot house, and generalizing it so that it can suit every house. The resulting model is named the Battery Ranking Model (BRM).

The best battery choice for a particular household varies largely depending on the requirements of the homeowner and the conditions of the households themselves. Thus, multiple questions are developed for the homeowners to answer so that the battery choice will be home-specific. Both the preliminary model and the BRM model are designed to evaluate the difference between the homeowner's expectations for the batteries and the batteries' actual specifications. In both models, the batteries will be ranked based on the differences of their specifications from the homeowners' expectations.

To evaluate the BRM, a sample 1600-square-foot household is set up. A set of fictional requirements, determined based on real-world situations, are also listed. The model is then tasked to choose from a list of 16 real-world battery examples of 5 different types. By ranking and comparing the top 3 "best" batteries using both models, the generality and the accuracy of the BRM are investigated. A sensitivity analysis for the data input and the weight of factors is conducted and presented to find potential sensitive factors.

The inclusion of emerging nonconventional batteries is also deemed important. An example of such batteries, a recently developed concrete-based battery, has the potential of bringing immense benefits when used in conjunction with conventional energy storages, as concrete is present in almost every contemporary building. The advantages and the disadvantages of the concrete battery are first listed, and the potential usages of the concrete battery are then identified. Yet, as this battery type is still at its rudimentary stage, there is not enough information to rank it using the BRM. Thus, information needed to make the battery classifiable is listed for future investigations to reference.

A news article is also written with the purpose of introducing the public to a new hope for battery users. In the article, readers can understand the latest battery-choosing model and the most unconventional battery, the concrete battery, with ease. Soon, they will realize that they will no longer baffle when choosing from a battery of batteries using the BRM. The best choice is only clicks away.

Key Words: Battery Ranking; Solar Energy; Renewable Energy; Concrete Battery

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1 Introduction

1.1 Problem Background

Human history can be seen as a never-ending search for better energy sources. Since the domestication of animals during prehistoric times, humans have moved from animals to coal, petroleum, liquefied natural gas, and now, renewable sources like the sun or the wind. Yet, unlike coal and petrol, the likes of solar and wind energy can not be effectively stored until the invention of the battery, a device that stores energy in the chemical form. The invention has since became an integral part of the mechanisms of a functioning world, powering devices ranging from watches to buildings.

Among the systems that harness renewable energy sources is one consisting solar panels, batteries, and a few supplementing devices. Solar energy from the sun is converted into electrical energy by photovoltaic cells within solar panels, and the energy is then converted into chemical energy to be stored in batteries. Charge controllers are often used to regulate the charging process to prevent overcharging, and inverters are used to convert the output of the batteries into user-friendly alternating currents. As such systems are renewable and emission-free, they are deemed by some as the future.

Able to harness solar energy, dreams of having fully autonomous off-the-grid homes at remote locations have materialized. By building a home at a place with enough sunlight, one can generate enough energy to support oneself, thereby eliminating the need to extract energy from the power grid. Yet, for such homes, having enough energy during nights and sunless days is crucial, making the selection of the right energy storage system, more specifically, the right battery, important. As there are dozens of possible candidates with distinctive specifications, the team's goal is to find a way to select the best battery for every remote home. Conditions such as nights and cloudy days, and the properties of the battery, such as continuous power rating, instantaneous power rating, usable capacity and round-trip efficiency, will be considered to make an accurate choice.

1.2 Restatement of Questions

- **Question 1:** To begin with, we should list our energy needs for choosing the battery in order to increase the comprehensiveness of our battery choice. We need to focus on meeting the homeowners' requirements and the battery itself. If we take time into consideration, for example, the chosen battery should have enough capacity to deliver during nights and cloudy days.

  Then, we should build a mathematical model to decide which battery to choose based on homeowners' requirements. We can put our considered factors into our model to get a result, which will show the magnitude of the differences between the batteries' properties and the homeowners' expectations. Hence, we can find a battery that fits with the conditions of the house and the requirements of the homeowners and find them the best battery choice.

- **Question 2:** We will modify and summarize our model to meet demands of other individual homeowners. For instance, different homeowners may require batteries of different dimension. By evaluating our model, we can find that there are many variables within.

- **Question 3:** Since researchers in Sweden have discovered that cement could be used to store energy, and it is widely used in a variety of buildings, we will find ways to implement this property in off-the-grid homes. We will identify the pros and cons of using cement as an energy storage device to determine whether it fits in off-the-grid homes, among other types of homes. We will also find additional information on cement to make comparisons between the novelty with conventional batteries in order to adjust our model to take concrete batteries into account.

- **Question 4:** Finally, we will present our solar power battery storage decision model in a user-friendly article. It will contain possible usages and functions of the traditional solar batteries and the concrete battery and will contain the advantages and disadvantages of such batteries. The article should also include insights to our model to ensure that even the uninitiated can make rational decisions.

1.3 Assumptions and Justifications

Several assumptions are listed to simplify the problem. The assumptions and their justifications are listed below.

- **Assumption 1:** There is sufficient solar energy to fully recharge the batteries and power the household at the same time during a sunny day.
  Justification: It is assumed that charging can be done within a sunny day to reduce the variables in the models. The scenario realistic for a remote household as there will be plenty of space to install sufficient solar panels to meet the demand.

- **Assumption 2:** The batteries and the sun are the only energy sources the households discussed are set to use.
  Justification: In a normal household, the energy consumed comes from a variety of sources including electricity, gas, and in some cases, petroleum. A remote, off-the-grid home, however, needs to use fully renewable sources to achieve autonomy. Therefore, the household is assumed to use electric devices only. For example, a gas fueled water heater found in a conventional home is assumed to be replaced by an electric counterpart that draws energy from batteries and solar panels.

- **Assumption 3:** The inside of a household is assumed to have a temperature of 25℃. The batteries are kept indoors.
  Justification: There is every reason to put the battery indoors, as they can be better protected from the less-than-ideal conditions outside. In addition, batteries, especially acid-based ones, usually work best under room temperature of 25℃, under which the rated capacities of most batteries are measured. Assuming that the batteries are kept indoors is not only realistic, but it also contributes to the simplification of the models.

- **Assumption 4:** The location of the household is assumed to have no influence on battery performance and the total energy consumed.
  Justification: As previously mentioned, the batteries are stored indoors and thus are not subjected to the external environment, which is usually determined by the location of the household. Thus, the household's location is assumed to be of no importance.

- **Assumption 5:** Energy loss from inverters and charge controllers is negligible.
  Justification: As previously mentioned, charge controllers are used to regulate the charging process to increase the lifespan of the batteries. Most of the batteries designed to store solar energy in terms of chemical energy have direct current (DC) outputs. Typical household devices, however, only accept an alternating current (AC) as input. Thus, inverters that convert DC into AC are usually implemented. Although energy will be lost due to the usage of such devices, the amount is negligible compared to losses due to other sources. Thus, the losses from such devices are not considered for the sake of simplification.

2 Model Design for 1600 Square-foot Off-the-grid Home

2.1 Variables

Variable Symbol	Meaning	Variable Symbol	Meaning
d_x	Disparity value for factor x	n	Number of batteries purchased
w_x	Weight of factor x	t_i	Working time of item i
D_x	Expectation for factor x	p_i	Working period of item i
R_x	Actual value for factor x	v_i	Value of item i
E_{dt}	Daily total energy	A_t	Set of all items
E_{dn}	Daily necessary energy	A_n	Set of necessary items
E_i	Daily energy used for item i	A_r	Set of random items
C_b	Battery price	S_t	Set of items working at t
C_{bt}	Battery total capacity	u	Usable capacity percentage
P_{bc}	Continuous power of battery	ρ	Efficiency of battery
P_i	Average power rate of item i	f	Capacity Fade
k	Days of autonomy	r	Rate constant
b	Maximum days under energy supply	a	Days that all items can work
		a_{opt}	a when benefit is maximized

Table 1: Variables in the Model

2.2 Factors Consideration

This section is intended to identify two categories of factors, energy factors and economic factors, that are considered important for selecting the "best" battery.

2.2.1 Energy Factors

1. **Capacity:** There is no doubt that the capacity of a battery is influential when choosing the "best" battery. To determine the expected capacity, we require user to provide **daily total energy** and **daily necessary energy**.
2. **Peak power rate:** It is the total power consumed when most electrical appliances are in use. Evidently, the "best" battery given by the model should be capable of supplying adequate power during peak hours.

2.2.2 Economic Factors

1. **Budget:** Solar storage batteries are rather expensive. The ability for a household to purchase batteries is worth considering in the model[14]. If the budget of one household is significantly less than the actual cost of a solar storage battery, the battery is certainty not suitable.
2. **Expected lifetime:** This is also a crucial factor to take into account. It is possible that the household can not afford to frequently replace degraded batteries. In this case, only a battery with a long lifetime would suit the requirement.
3. **Maintenance:** Due to poor finance condition, a resident may not be capable of affording regular maintenance services. In this circumstance, a battery, such as a lithium iron phosphate battery, that does not require maintenance is an appropriate choice.

2.3 List of Energy Demand Questions

It may be hard for users to calculate the daily total energy and the peak power rate. We therefore make a list of questions to help users determine their daily energy needs.

1. **What electrical appliances need energy?** There is no doubt that all electrical appliances consume electricity, and that's how energy needs arise. Therefore, knowing every electrical appliance is an indispensable step to determine energy needs. We also design the following questions to further identify the attributes of each appliance.
    (a) **Is the appliance necessary or optional?** The importance of each appliance in daily life may have an impact the output of our model. The inevitability to shut down some unnecessary electrical appliances has been investigated earlier, so whether the appliance is necessary or optional is influential to the final result.
    (b) **Does the appliance work periodically?** Certain appliances such as cookers usually work periodically, while other items such as heat bottles tend to operate at various times in a day. Thus, we categorize every appliance into two types: periodic appliance that work at predictable time periods, and random appliance, of which the working time is more likely to be flexible.
    (c) **If the appliance works periodically, when does the appliance work?** For periodic appliances, users have to provide the working hours of these appliances in order for the model to compute the daily energy use as well as peak power rate at different periods.
    (d) **If the appliance works at random times, what is the average working time every day?** With regard to random appliances, the accurate working time cannot be given because of their irregular usages. Therefore, we require users to input the mean working hours every day to estimate the daily energy use.
    (e) **What is the average power rate of the appliance?** The power rate of the appliance is one of the most crucial factors that must be considered. Both the calculations of peak power rate in a day and the total daily energy use require the power of every electrical appliance to be known.
    (f) **What is the value of the appliance?** The value of the appliance is the benefit that it can bring to users when in use. To quantify this factor, we develop a scale from 1 to 9, for which 1 represents little benefit and 9 represents considerable benefit the appliance brings. Notice that the value of appliance is not related to the necessity of it. For instance, air conditioning can be optional for the household, whereas it brings a lot comfort for people in the house.
2. **What is your expected days of autonomy?** When encountering sunless days, the solar panel cannot capture and obtain solar energy, so the storage battery is responsible for supplying electricity for all appliances. As the sunless condition may last more than one day, the expected days that the battery can independently supply energy must be given by the user.

2.4 Approach

To find out the "best" battery for the 1600 square-foot off-the-grid home, one essential step is to quantify the suitability of each battery and rank all batteries to seek out the "best" one with the highest suitability. After consideration, we decide to take the disparity (d) of desired value (D) and realistic value (R) for each factor. By adding every disparity value for all factors, the overall disparity is produced. The higher the disparity, the less suitability of the battery for the household. Therefore, the solar battery with the least overall disparity is selected as the "best" battery for our 1600 square-foot off-the-grid home.

The formulae of calculating disparity values for different factors may not be totally the same. Hence, for each factor, we will discuss and provide an algorithm to obtain the disparity value.

2.4.1 Capacity

Before calculating the expected battery capacity, it would be necessary to beforehand determine the value of daily total energy and daily necessary energy using the various attributes and other data of all electrical appliances in the off-the-grid home provided by the user.

To begin with, we can consider the energy needed for each electrical appliance. For appliance i, the daily energy consumed, E_i, is

$$E_i = P_i t_i \tag{1}$$

where P_i refers to the average power rate of the appliance when in use, and t_i is the daily working time. Note that this equation is applicable for both periodic and random appliances, as only the working hours of appliances is needed, which, for both types of appliances, has been given by users. The daily total energy is the sum of the energy used up by all the appliances, which can be described as Equation (2).

$$E_{dt} = \sum_{i \in A_t} E_i = \sum_{i \in A_t} P_i t_i \tag{2}$$

Regarding to daily necessary energy use, E_{dn}, the same method can also be employed, but the appliances all belong to A_n, the set of necessary appliances in the house.

$$E_{dn} = \sum_{i \in A_n} E_i = \sum_{i \in A_n} P_i t_i \tag{3}$$

After the acquisition of E_{dt} and E_{dn}, it is now feasible to compute the expected capacity of the battery. If a battery is incapable of supplying sufficient energy to all appliances for a few days, only necessary appliances can operate and other optional ones must be given up in the case of consecutive sunless days. Assume that the user demands k days of autonomy, and there are a days that all appliances can work, and for the other $k - a$ days, only necessary appliances can be in use. Yet a battery must still have enough capacity even after a few years. If a battery is heavily drained, the battery's capacity will fade fast and will not last. These two variables are the major sources of energy loss. Since the desired battery capacity should be less than or equal to the actual one, the following inequality can be established.

$$D_C = \frac{aE_{dt} + (k-a)E_{dn}}{u\rho(1-f)} \leq R_C = nC_{bt} \tag{4}$$

where u is the usable capacity percentage, or depth or discharge, which is the maximum proportion of energy that can be discharged, as extensive discharging will be harmful to battery health and reduce lifetime[15], ρ is the round-trip efficiency of the battery, and f is the capacity fade of battery over time, which is necessary as any battery will degrade. The left hand side shows how expected capacity is determined. On the right hand side of the inequality, n refers to the number of batteries purchased, as some batteries need to be packed in order to have adequate energy, and C_{bt} is the total capacity for one battery.

Since the efficiency or the remaining percentage of the battery capacity cannot be negative, the sign of inequality doesn't change. By solving this inequality, a can be deduced. To optimize the benefit of brought by the appliances, a should be maximized. Consequently, the rounded down maximum value of a is the final number of days that all appliances can operate. We label it a_{opt}. The below equation gives how a_{opt} is deduced.

$$a_{opt} = \left\lfloor \frac{nu\rho(1-f)C_{bt} - kE_{dn}}{E_{dt} - E_{dn}} \right\rfloor \tag{5}$$

For different ranges of a_{opt}, the disparity value varies.

1. $a_{opt} \geq k$**:** When the optimum a is larger than days of autonomy, the battery can supply adequate electricity to all household appliances for desired duration. Thus, the battery capacity fulfills the requirement of energy use, and the disparity value, d_C, should be zero.

2. $0 \leq a_{opt} < k$**:** For most situations, we must sacrifice the use of some unnecessary electrical appliances to keep other items of greater importance working. In the first a_{opt} days, all appliances can operate, thereby the disparity value for those days is zero. However, for the other $k - a_{opt}$ days, a non-zero disparity value exists. To evaluate d_C, we choose to use the total value of necessary appliances and of all appliances. The greater the total value of necessary appliances is, the less the disparity is. We consider Equation (6) as the disparity formula.

   $$d_C = r_1 \left(\frac{\sum_{i \in A_t} v_i}{\sum_{j \in A_n} v_j} - 1 \right)^2 (k - a_{opt}) \tag{6}$$

   where v represents the value of an appliance, and r is a rate constant.

   The equation can be interpreted as the square of percentage of total value of all appliances more than total value of necessary appliances, times the number of days of only using necessary appliances. This accords with our anticipation, as the higher proportion of benefit the necessary appliances brings compared to the total benefit, the lower the calculated disparity is.

3. $a_{opt} < 0$**:** Nevertheless, some batteries can't even power all essential appliances for k days. But, if the time without electricity is relatively small, it is still acceptable for users to endure power outages. In this case, Equation 6 is still applicable to calculate the disparity value.

   First, it is necessary to determine the maximum number of days with energy supply. Let this number be b, which can be calculated as the ratio of usable capacity of the battery and daily necessary energy, and can be expressed as follows.

   $$b = \frac{nu\rho(1 - f)C_{bt}}{E_{dn}} \tag{7}$$

   If the requirement $b \geq k - 0.5$ is satisfied, indicating that for half of the last day, the available energy in the battery is used up and all appliances will stop working, we believe that for users, it is in the acceptable range, and we can still use Equation 6 to determine d_C. Yet, if $b < k - 0.5$, we consider that it is intolerable for users to survive for such a long period without electricity supply. Hence, we set the disparity value to infinity so that this battery pack will never be selected as the "best" battery.

In all, the algorithm that determines the disparity value for battery capacity is shown as Equation (8).

$$d_C = \begin{cases} 0 & , a_{opt} \geq k \\ r_1 \left(\frac{\sum_{i \in A_t} v_i}{\sum_{j \in A_n} v_j} - 1 \right)^2 (k - a_{opt}) & , 0 \leq a_{opt} < k \quad or \quad b \geq k - 0.5 \\ \infty & , b < k - 0.5 \end{cases} \tag{8}$$

2.4.2 Peak Power Rate

Another crucial energy factor is the peak power rate. If the battery cannot supply adequate electricity when most power is demanded, the excess demand of power may result in power outages, which is undesirable for residents. As a result, assessing the availability for a battery to offer a peak power rate is also crucial.

At an arbitrary instant t, in hours, the total power rate is the sum of the power of all appliances that is running at that time. It can be written as Equation (9), as shown below.

$$P_t = \sum_{i \in S_t} P_i \tag{9}$$

where P_t is the total power rate at time t, P_i refers to the average power of appliance i, and S_t is a set of appliances such that they are operating at time t. In mathematical form, S_t can be expressed as

$$S_t = \{j | t \in p_j\} \tag{10}$$

Therefore, by comparing the total power rate at all instants, the maximum value can be identified and the value is the most likely one to be the peak power rate. Nonetheless, for the random appliances, which do not have a fixed working time p, the method above is inapplicable. To take the worst situation into account, that all random appliances are running at instant t, we have to add the total average power rate of all random appliances. Eventually, the maximum value gained by comparing P_t at all instants t plus total power rate of random appliances is the desired peak power rate. Equation (11) presents how D_P, the desired peak power rate, is calculated.

$$D_P = \max_{t \in [0,24)} P_t + \sum_{j \in A_r} P_j = \max_{t \in [0,24]} \sum_{i \in S_t} P_i + \sum_{j \in A_r} P_j \tag{11}$$

where A_r is a set of random appliances in the off-the-grid home.

To determine the actual continuous power of a battery, we only need to multiply the power of a single battery with the number of batteries actually purchased. Equation (12) expresses how R_P is obtained mathematically.

$$R_P = nP_{bc} \tag{12}$$

Given the actual continuous power of battery, R_P is greater than the anticipated one, D_P, the requirement is met, and no disparity exists. On the other hand, if the requirement not met, a d_P is present. To assess this disparity, we take the square of the percentage difference between the expected peak power rate and that of the actual battery as the disparity value. The reason why we use square is that if the actual peak power is slightly larger than the anticipated one, d_P will not tend to be significantly large, and as this percentage increases, the disparity value will increase rapidly, meaning that the battery is less desirable for the household. Overall, the equation of d_P can be written as follows.

$$d_P = \begin{cases} 0 & , D_P \le R_P \\ r_1 \left(\frac{D_P - R_P}{R_P} \right)^2 & , D_P > R_P \end{cases} \tag{13}$$

2.4.3 Budget

As previously mentioned, the economic condition of the household will also affect the final choice of the "best" battery. However, for some lead-acid batteries, a battery pack is required to supply sufficient energy to households. We use n to represent the number of batteries purchased, and the actual value of the budget in terms of n is

$$R_B = nC_b \tag{14}$$

where C_b refers to the cost of one battery. As n is not given, and it is currently not practical to calculate the value of n when the overall disparity is minimized, we can only acquire an approximate range of n in which the optimal one may lie. The minimum n is evidently 1. The maximum value requires discussion. If the total capacity of the battery pack allows all appliances to operate for k days, the capacity requirement has been satisfied and the disparity value for this factor is zero, which is minimized. The same deduction can be applied for continuous power rate. If the actual continuous power is higher than the expected one, users do not have to buy any more batteries. It can be reasonably inferred that the minimum number of batteries required to fulfill both the capacity and the peak power requirements is the maximum n. Given Formula (4), the maximum number of batteries, n_{max}, is

$$n_{max} = \max \left\{ \left\lceil \frac{D_{C\max}}{C_{bt}} \right\rceil, \left\lceil \frac{D_{P\max}}{P_{bc}} \right\rceil \right\} \tag{15}$$

From common sense, if the price of a battery is too high for the residents to afford, the choice is not preferable. Thus, different from the factors introduced before, the actual cost of the batteries is desired to be lower than the budget. If this demand is attained, the disparity value should equal zero. Conversely, the disparity value emerges when the demand is not achieved. To summarize, Equation (16) shows how d_B is calculated.

$$d_B = \begin{cases} 0 & D_B \geq R_B \\ r_2 \left[\left(\frac{R_B}{D_B} \right)^{\frac{3}{2}} - 1 \right] & D_B < R_B \end{cases} \tag{16}$$

For different numbers of batteries purchased, the overall disparity value will vary. As the choice of n only impacts budget, power and capacity factor, to select the optimal one, n_{opt}, the sum of the disparity values for budget and capacity factor should be minimized. Equation (17) best illustrates the method of acquiring n_{opt}.

$$n_{opt} = \underset{n \in [1, n_{max}]}{\arg\max} \{ w'_C d_C + w'_P d_P + w'_B d_B \} \tag{17}$$

where w'_C, w'_P and w'_B are normalized weights of each respective factor, which will be discussed in later sections. The optimal disparity value for capacity and budget factors will occur when n_{opt} batteries are bought.

2.4.4 Lifetime

Discussions regarding lifetime are very similar to those regarding power rate, and the algorithm regarding lifetime is much simpler than that regarding power rate, for there is no need to consider the number of batteries purchased. The algorithm for lifetime is shown as Equation (18).

$$d_L = \begin{cases} 0 & D_L \leq R_L \\ r_1 \left(\frac{D_L - R_L}{R_L} \right)^2 & D_L > R_L \end{cases} \tag{18}$$

2.4.5 Maintenance

For the maintenance factor, we only consider whether the batteries require maintenance and the users' attitude toward maintenance. If the user accepts maintenance costs, then for the maintenance factor, the disparity value is always zero; if the user declines maintenance costs and the battery requires maintenance, we set a value of 10 as disparity value d_M. Table 2 gives how d_M is determined.

		Battery	
		Require Maintenance	Maintenance Free
User Attitude	Accept	0	0
	Decline	10	0

Table 2: Disparity Value for Maintenance Factor under Various Circumstances

2.4.6 Calculation of Rate Constant

In previous subsections, we employ two rate constants: r_1 and r_2. Doing so allows us to manipulate the rate of increase in disparity value. In this subsection, we will deduce the values of r_1 and r_2.

It can be observed that r_1 appears only when expectation is greater than the actual value, which results in a disparity. To control the rate of increase, we hypothesize that provided the expectation is 20% greater than the actual one, the disparity value is 1. This is reasonable because if the expectation is slightly larger than the actual value, it is in the bearable range, and the disparity value will not be too high. According to this hypothesis, the following equation of r_1 can be constructed.

$$r_1\left(\frac{1.2R-R}{R}\right)^2 = 0.04r_1 = 1 \tag{19}$$

We can easily see that the value of r_1 is 25.

With respect to r_2, which exists only when the actual value is greater than expectation, leading to a disparity, we presume that given the D is 10% less than R, the disparity value is 1, as people are usually value the budget factor as important. Using same method, r_2 can be deduced.

$$r_2\left(\left(\frac{R}{0.9R}\right)^{\frac{3}{2}} - 1\right) = 0.171r_2 = 1 \tag{20}$$

The value of r_2 is determined to be 5.84.

2.4.7 Overall Disparity Value

After calculating the disparity value for each single factor, computing the overall disparity value is viable. Yet, various users have diverse priorities with respect to different factors. To resolve this problem, we request users to input the weight of each factor, w_x, to illustrate the priority of each factor. Table 3 shows the degree of importance for each calibration.

Weight	Meaning
1	Very unimportant
3	Somewhat unimportant
5	Neutral
7	Somewhat important
9	Very important
2, 4, 6, 8	In between

Table 3: Meaning of different weight for factor

To demonstrate a more accurate result, we will first normalize the weight and then calculate the total disparity value. For weight w_i, the normalized value of weight is

$$w_i' = \frac{w_i}{\sum w_x} \tag{21}$$

Finally, the overall disparity value is

$$d = \sum w_x' d_x \tag{22}$$

Notice that the product of weight and disparity value for each factor can simply add up because they are of the same scale. The weight is normalized and the disparity value is obtained from the ratio of expectation to the actual value, which is a percentage. Ultimately, the battery with the least overall disparity value is the output of the model, which is the "best" battery for the 1600 square-foot off-the-grid home.

3 Extended Model: Battery Ranking Model (BRM)

The model for selecting "best" battery for a 1600 square-foot off-the-grid home has considered various factors that may influence the final choice. However, some relatively less important factors for the off-the-grid home were either partially discussed or not discussed at all. To better adapt our model to individual needs, we will modify our model by taking three more factors into account - dimension, safety, and additional cost.

3.1 Variables

Variable Symbol	Meaning	Variable Symbol	Meaning
d_x	Disparity value for factor x	l_b	Length of one battery
w_x	Weight of factor x	n_d	Batteries placed in direction d
D_x	Expectation for factor x	s	Safety value
R_x	Actual value for factor x	r_2	Rate constant
n_{opt}	Optimum n with least d	C_t	Other expenses

Table 4: Variables in BRM

3.2 Factors Consideration

1. **Dimension:** A 1600 square-foot off-the-grid home is large enough to accommodate solar storage batteries. However, for smaller residences, the space for batteries may be limited. The length, width, as well as height of the battery pack should all be less than the desired dimension for placing the battery.

2. **Safety:** This is also an essential factor that many homeowners may pay attention to. Some batteries may have special requirements; if they are installed inappropriately, there may be potential safety hazards, resulting in blackouts or even explosions. Evidently, safety is also a factor that needs to be well considered.

3. **Transportation and Installation Cost:** For different households, due to their different locations, the labour expense varies. For downtown areas, the transportation cost tends to be low, while for suburbs, the countryside, and other remote places, the cost would be high. Consequently, the labour expenses should also be included in the model.

3.3 Approach

Despite some modifications and generalizations, the overall approach to find the "best" battery is still the same - determining the total disparity value. Hence, we will use the same means to compute the disparity value for the dimension and the safety factor. As two new factors (dimension, safety. Additional cost is considered in budget factor) are included in the BRM, the user must provide the weight of those two factor so that the model can identify the importance of each factor comprehensively.

3.3.1 Dimension

Dimension is not only a number; it consists of length, width and height. this indicates that for each component of dimension, we all have to come up with an algorithm to obtain the disparity value.

One issue that worth discussion is the number of batteries purchased. The greater the n, the larger the space required for installing the batteries is. Given the number of batteries placed horizontally and vertically, namely n_l, n_w, n_h, it must satisfy Equation (23).

$$n_l \times n_w \times n_h \geq n \quad , 1 \leq n_l, n_w, n_h \leq n \tag{23}$$

One basic requirement for the three variables is that they must all be positive integers. The expected value for one component of dimension, for example, length, is

$$D_l = n_l l_b \tag{24}$$

where l refers to the length of battery. As a matter of experience, users certainly want a battery with a length less than their anticipations. Therefore, the actual length of the battery is desired to be less than the expected one. Similar to lifetime, we provide Equation (25) as the algorithm for the disparity value for the length factor.

$$d_l = \begin{cases} 0 & D_l \geq R_l \\ r_2 \left[\left(\frac{R_l}{D_l} \right)^{\frac{3}{2}} - 1 \right] & D_l < R_l \end{cases} \tag{25}$$

The algorithms for width and height factors are similar to that for the length factor, but the parameters are replaced by the expected and actual width and height, respectively.

To sum up the disparity value for dimension factor, we take the minimum average value of the three disparity values for the components of dimension as the final disparity value, given a range of n_l, n_w, and n_h.

$$d_D = \min \frac{d_l + d_w + d_h}{3} \tag{26}$$

3.3.2 Budget

Since the number of batteries is also considered in the dimension algorithm, Equation (17) is modified as follows to optimize disparity value and to determine the optimum number of batteries.

$$n_{opt} = \underset{n \in [1, n_{max}]}{\arg\max} \left(w'_C d_C + w'_P d_P + w'_B d_B + w'_D d_D \right) \tag{27}$$

Also, since other expenses such as transportation and labour cost is taken into account, the actual cost, R_B, should include those extra expenses. Equation (28) describes the expression of new R_B.

$$R_B = nC_b + C_t \tag{28}$$

where n is the number of batteries purchased, C_b is the raw cost of one battery, and C_t represents the other expenditures required to transport and install the batteries. The rest of the algorithm remains unchanged.

3.3.3 Safety

In fact, all solar batteries are verified to be safe across technologies[16], whereas most safety hazards are due to improper usages, such as acid leaks or short circuits. We therefore artificially define a safety value s to indicate how safe a battery is. The higher the safety value, the safer the battery. This is a relative value assigned to make comparisons with other batteries. However, it is quite hard to determine s, as the chemistry and the mechanism of every battery varies. To resolve this issue, for the same type of batteries, for example, sealed lead acid (SLA) batteries, we will set a constant value. This manifests that only different types of batteries have different safety values. Table 5[16][17][18] shows the safety values for all types of solar batteries.

Types of Battery	Safety Value
NMC	1
LFP	2
LTO	2
SLA	2.5
GEL	3

Table 5: Safety Values for Different Types of Batteries

$$d_S = r_2 \left[\left(\frac{s_{max}}{s} \right)^2 - 1 \right] \tag{29}$$

To assess the disparity value for the safety factor, Equation (29) is established as the algorithm for safety factor.

In the equation, s_{max} is the maximum safety value among all types of batteries, which is 3, and d_S is the disparity value for safety factor. This algorithm is consistent with our expectation, as the less safety value is, or the more dangerous a battery is, the larger the disparity value will be.

4 Data Collection

4.1 Battery Data

In order to make comprehensive choices, more than a dozen of batteries of five different battery types are considered. The data for the batteries are listed in Table 6.

Battery	Total Capacity (kWh)	Usable Capacity (%)	Power Output (kW)	Type	Lifetime (Years)	Capacity Fade (%)	Cost ($)	Size (mm)	Efficiency (%)
Tesla Powerwall 2	13.5	90	5	NMC	10	30	12015	1150 × 753 × 147	90
LG Chem RESU Series	13	90	5	NMC	10	40	9594	626 × 452 × 227	/
LG Chem RESU H Series	9.8	90	3.5	NMC	10	40	7526	907 × 744 × 206	95
Varta Pulse 6	6.5	90	2.5	NMC	10	30	7150	690 × 600 × 186	90.5
Sonnen ECO	16	100	3	LFP	10	40	19008	2117 × 651 × 483	86
Senec Home Li 10	10	95	2.5	LFP	10	20	11850	1120 × 530 × 400	95
BYD B-BOX Pro	2.54	100	2.54	LFP	10	40	1803	1728 × 620 × 320	/
Simpilphi PHI	3.4	100	1.7	LFP	10	20	3445	356 × 343 × 203	/
GenZ LFP	3	100	1.5	LFP	10	20	2364	420 × 570 × 88	/
Zenaji Aeon	1.93	100	2.5	LTO	20	20	3078	1635 × 155 × 145	96
SIRIUS SuperCap	3.55	100	5	LTO	10	20	5094	600 × 534 × 200	99.1
MightyMax Battery 12V 75Ah	0.9	/	0.12	SLA	1	/	140	168 × 260 × 230	/
Renogy Deep Cycle AGM Battery	2.4	/	0.12	SLA	2	/	372	240 × 224 × 522	/
Rolls Surrette S2-1275	2.3	/	0.02	SLA	7	/	685	424 × 295 × 179	/
Yangtze Solar 6-GFM-150	1.8	/	0.12	SLA	3	/	140	241 × 486 × 171	/
CSPower GEL Battery	1.32	/	0.12	GEL	3	/	120	176 × 331 × 220	/

Table 6: Battery Data[1][2][3][4][5][6][7][8][9][10][11][12][13]

On account of scarce data sources, we can only find a portion of accessible battery properties. Regarding to efficiency, lead acid batteries (SLA and GEL) usually have a 70% energy efficiency[19], while for other lithium-ions batteries, we can only presume their efficiency is 100%. For capacity fade, we reckon that when the battery is beyond its lifetime, it has a 40% capacity fade due to degradation. Finally, we consider the usable capacity for lead acid batteries is just 50%, as this is a safety factor to avoid over discharge.

Moreover, for non-lithium batteries (SLA and GEL batteries), the continuous current output varies depends on the duration of usage, resulting in varying continuous power ratings. Thus, the average amperage output for such batteries, 10A, is used to calculate the continuous power ratings of SLA and GEL batteries.

4.2 Data for a 1600 Square-Foot Home

The data for the energy-consuming devices in the 1600 square-foot home is listed in Table 7[20]. Whether a particular appliance is necessary or optional, periodic or random, its value, and its period of usage, are also listed. These values are determined based on common sense. Note that an appliance can be both necessary and periodic.

Appliance	Power (kW)	Working Period/Time	Necessary	Periodic	Value
4 Light Bulbs	0.4	17:00-23:00	1	1	9
Electric Stove	2	8:00-8:30, 12:00-12:30, 18:00-18:30	1	1	7
Refrigerator	0.055	0:00-24:00	1	1	8
Air Conditioning	0.2	0:00-6:00, 23:00-24:00	0	1	8
Washing Machine	2	10:00-12:00	0	1	4
Water Heater	4	21:00-21:30	0	1	6
Toaster	1.2	8:00-8:30	0	1	3
Electronic Devices	0.5	4 hours	1	0	9
Water Dispenser	0.03	24 hours	0	0	9

Table 7: Appliances Data

In Table 7, requirements by a typical homeowner of a 1600 square-foot home is stated. The "best" battery will be chosen based on the homeowner's requirements and the data for the homeowner's home.

Daily Energy	Necessary Energy	Peak Power	Lifetime	Budget	Days of Autonomy	Maintenance Attitude	Dimension	Other Expenses
17.44kWh	8.72kWh	4.455kW	5 Years	$12000	3 Days	Accept	$1m \times 1m \times 1m$	$1000

Table 8: Requirements of a Homeowner

Also, we subjectively determine the weight of energy and economic and other factors, listed in Table 9.

Capacity	Peak Power	Budget	Maintenance Attitude	Lifetime	Dimension	Safety
9	7	8	7	7	4	9

Table 9: Weight of Each Factor

5 Model Application and Analysis

5.1 Potential Candidates

Before using model developed for the 1600 square-foot household, some potential batteries can be roughly identified based on the requirements of the homeowner and the specifications of the batteries.

First, some battery choices can be eliminated as such batteries have specs that obviously deviate from the requirements. For example, Sonnen ECO is an obvious elimination as its $18000 price tag far exceeds the budget of $12000. The likes of Tesla Powerwall 2, LG Chem RESU H Series and Senec Home Li 10 are also not chosen for they have insufficient capacities despite their smaller price tags. Using this insight, it can be deduced that the homeowner's budget of a mere $12000 is insufficient for most lithium-based batteries, as a budget of $12000 is incapable of buying NMC, LFP and LTO batteries with a combined capacity of above the minimum daily energy requirement of 17.44kWh, as stated in Table 8. Thus, only acid-based batteries are possible candidates under this limited budget.

Upon evaluating the five acid-based batteries of SLA and GEL types, it can be seen that although such batteries have comparatively inexpensive prices, their claimed capacities and continuous powers are relatively small. The Rolls Surrette S2-1275, for example, has a continuous power output small enough for it to be excluded from the comparison. Nevertheless, for the other four batteries, it is possible to buy multiple units to yield a combination that satisfies the homeowner's demands. It should be noted that for acid-based batteries, or the so called "deep cycle batteries", the required peak power is not a concern as such batteries are more than ten times more capable in terms of delivering peak power. Yet, the lifetime of some of the batteries, such as that of MightyMax Battery and Renogy Deep Cycle AGM Battery, is too short, and thus, such batteries should not be considered, leaving the Yangtze Solar 6-GFM-150 and CSPower GEL Battery the only potential candidates after a rough analysis.

5.2 Data Substitution

5.2.1 Model for 1600 Square Off-the-grid Home

To accurately find out the "best" battery for the 1600 square-foot home, we plug the battery, appliance, expectation data as well as weight for each factor in the model to assess the disparity value. We take Tesla Powerwall 2 as an example battery.

Firsthand, we will deduce the normalized weight for each factor. For instance, with regard to weight of capacity, the normalization process is shown as Equation (30).

$$w'_C = \frac{w_C}{\sum w_x} = \frac{9}{9+7+8+7+7} = 0.237 \tag{30}$$

Via the same approach, the normalized weights of factors can also be deduced, which are gathered in Table 10.

Capacity	Power	Budget	Maintenance Attitude	Lifetime
0.237	0.184	0.211	0.184	0.184

Table 10: Normalized Weights of Energy and Economic Factors

Next, we will determine the value of a_{opt} and b. Using Equation (5) and (7), a_{opt} and b can be expressed in term of n, the number of batteries purchased.

$$a_{opt} = \left\lfloor \frac{n \times 0.9 \times 0.9 \times (1-0.3) \times 13.5 - 3 \times 8.72}{17.44 - 8.72} \right\rfloor = \left\lfloor \frac{7.6545n - 26.16}{8.72} \right\rfloor = \lfloor 0.878n \rfloor - 3 \tag{31}$$

$$b = \frac{n \times 0.9 \times 0.9 \times (1-0.3) \times 13.5}{8.72} = \frac{7.6545n}{8.72} = 0.878n \tag{32}$$

By doing simple calculation, when n equals to 7, the battery pack can supply enough energy to all appliances for 3 days, where the corresponding disparity value is zero. When n becomes 4, if merely all necessary appliances work, the off-the-grid home can be under energy supply for 3 days. If n is even less than 3, user demand is sparsely fulfilled and disparity value increases to infinity.

The total values for all and necessary appliances are 63 and 42, respectively; hence, the disparity value for capacity factor, after simplification, according to Equation (8), is

$$d_C = \begin{cases} 0 & , n \geq 7 \\ 31.25\lfloor 0.878n \rfloor & , 3 \leq n < 7 \\ \infty & , n < 3 \end{cases} \tag{33}$$

As n has not been given, we can't currently assess the exact value of disparity value for capacity factor.

For peak power, according to Equation (13), as one Tesla Powerwall 2 battery has been outnumbered the peak power, the disparity value for power is always zero.

Now it comes to budget. Since 7 batteries is sufficient to provide energy for all electrical appliances in the house, the range of optimum n lies from 1 to 7. For each possible n, we compute the sum of weighted disparity values for capacity, power and budget factors. The result is shown in Table 11. We remove the columns when $n = 1$ or $n = 2$ because the disparity value for capacity factor is infinity, which means it will never be selected.

Factor	3	4	5	6	7
Capacity	18.75	18.75	12.5	6.25	0
Power	0	0	0	0	0
Budget	24.6	41.0	59.6	80.2	103
Total	9.61	13.1	15.5	18.4	21.6

Table 11: Disparity Values for Different n

Rank	Battery Name	Disparity
1	Yangtze Solar 6-GFM-150	3.36
2	CSPower GEL Battery	4.01
3	GenZ LFP	5.64

Table 12: Top 3 "Best" Batteries from Model for 1600 Square-foot Off-the-grid Home

If can be observed that when 3 batteries are purchased, the disparity value is minimized. Therefore, n_{opt} equals to 3.

With regard to maintenance attitude, as the homeowner accepts battery maintenance, the disparity value for maintenance attitude is zero. For lifetime, since the battery has a 10-year lifetime, which is longer than the expected one 5, the disparity value is also zero. Ultimately, the overall disparity value, d, for Tesla Powerwall 2 is 7.16.

For the other batteries, the same method is applied to obtain disparity value. We take the top three batteries with least disparity value as the "best" battery options, listed in Table 12.

5.2.2 BRM

BRM requires two additional information and weight - dimension and safety. We still take Tesla Powerwall 2 as a typical battery example to calculate the disparity values for the two extra factors and overall disparity value.

Since two more weights are added, we have to first re-normalize each weight of factor. Via the same approach, the new normalized weights are presented in Table 13.

Capacity	Power	Budget	Maintenance Attitude	Lifetime	Dimension	Safety
0.176	0.137	0.157	0.137	0.137	0.0784	0.176

Table 13: Normalized Weights of All Factor

Owing to considerations for the dimension factor in BRM, which is related to n, we have to re-enumerate the number of batteries purchased and calculate the total disparity value again. The results are collected in Table 14.

It can be easily deduced that the optimal number of batteries is 3, and the corresponding total disparity value for the four factors is 7.20.

For the safety factor, as Tesla Powerwall 2 is a lithium nickel manganese cobalt oxide (NMC) battery, which, according to Table 5, has a safety value of 1, the disparity value for this factor is

$$d_S = 5.84 \times \left[\left(\frac{3}{1} \right)^{\frac{3}{2}} - 1 \right] = 24.5 \tag{34}$$

Eventually, the final disparity value can be gained.

$$d = 7.40 + 0.176 \times 24.5 = 11.72 \tag{35}$$

Also for each battery, the overall disparity value is obtained and ranked, shown in Table 15.

Factor	3	4	5	6	7
Capacity	18.75	18.75	12.5	6.25	0
Power	0	0	0	0	0
Budget	25.8	42.4	61.2	81.9	104
Dimension	0.454	0.454	0.454	0.539	0.990
Total	7.40	10.0	11.8	14.0	16.5

Table 14: Disparity Values for Energy and Economic Factors

Rank	Battery Name	Disparity
1	Yangtze Solar 6-GFM-150	3.29
2	CSPower GEL Battery	3.41
3	GenZ LFP	5.21

Table 15: Top 3 "Best" Batteries from BRM

5.3 Evaluation for BRM

We will assess the performance of BRM in a variety of aspects.

5.3.1 Comparison between Models for 1600 Square-foot Off-the-grid Home and BRM

Although two models are very alike, because they are both intended to calculate the overall disparity value for each battery, and rank all batteries according to their disparities, due to consideration of other additional factors, size of the battery and safety, BRM tend to be more general, accurate and descriptively realistic than the other model. The result in previous section is a strong evidence. Using the model for 1600 square-foot off-the-grid home, Yangtze Solar 6-GFM-150 is obtained to be the "best" solar battery for the home, while CSPower GEL Battery is next "best", with a comparatively big difference of 0.65. However, in BRM, The difference disparity value of Yangtze Solar 6-GFM-150 and CSPower GEL Battery drops to 0.12, which is significantly lower. This is because CSPower GEL Battery is smaller and safer than Yangtze Solar 6-GFM-150; therefore the dimension and safety factor plays a role in reducing the gap.

5.3.2 Sensitivity Analysis

We divide sensitivity analysis into two parts - data input of user and weight of each factor.

Data Input To assess the sensitivity of data input from user, we give an error range from -10% to 10% and calculate the mean percentage error of overall disparity value. We use the following equation as the formula of quantifying mean percentage error.

$$e_i = \frac{\sum \frac{|d_{xi} - d_{x0}|}{d_{x0}}}{n_b} = \frac{\frac{1}{d_{x0}} \sum |d_{xi} - d_{x0}|}{n_b} \tag{36}$$

where e_i is the mean percentage error when a factor has an error of $i\%$, d_{xi} is the overall disparity value for appliance x given an error of $i\%$, d_{x0} is the disparity value when no error exists, and n_b is the number of available battery options. For each factor, we employ the above equation to deduce the percentage error and plot the results in Figure 1.

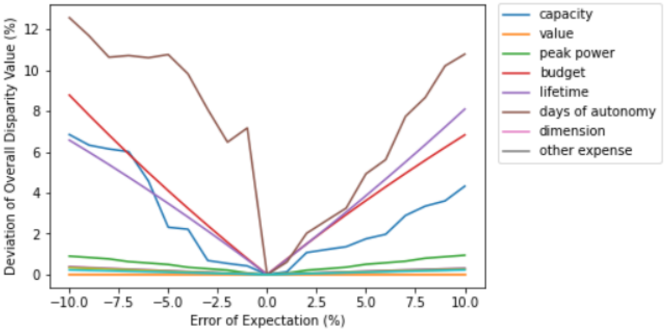

Figure 1: Sensitivity Analysis for Data Input

As can be seen on the figure, for most factors, including value of appliances, capacity, peak power, dimension, other expenses and so on, a percentage change in expectation of each factor cause a small percentage change in final disparity value. This implies that our model is very robust to expectation of most factors.

Weight of Factors Though we have given a scale for user to help assess the importance of each factor, it may still be inevitable that this includes error, and thus the significance of sensitivity analysis for weight of factors arises. We also employ Equation (36) to find out the responsiveness of disparity value with respect to variation in weight of each factor.

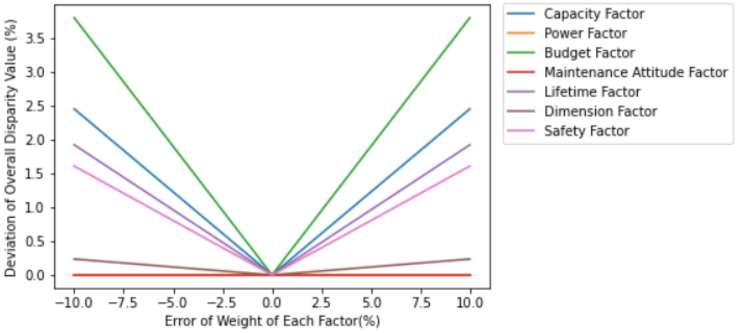

Figure 2: Sensitivity Analysis for Weight of Factors

The percentage deviation resulting from inaccuracy of weight, from Figure 2, is deduced to be small. This implies that the model is also very insensitive to weight of factors.

6 Assessment and Outlook of Concrete Battery

Most contemporary buildings, including skyscrapers and bridges, are built from reinforced concrete for its excellent ability to cope with physical stresses over distance, which could not have been achieved with concrete alone. Reinforced concrete refers to a structure in which wire meshes are embedded concrete, and together, the two materials can cope with much greater strains due to the combination of their distinct properties. As cement is present in large amounts, scientists have been keen on exploring the possibility of utilizing such structures as huge energy storage devices. A recent study has shown that it is indeed possible to build a rechargeable "concrete battery" or "cement battery"[21], making it possible to turn entire buildings into powerbanks.

The authors of the study investigated and built a concrete-based rechargeable battery with a "layered structure" that consists three layers: a cement-based anode, a cement-based separator separating the cathode and the anode, and a cement-based cathode. Carbon fiber coated with nickel and uncoated carbon fiber that acts as current collectors are embedded within the cathodes and the anodes. The "metal coating" structure is claimed to have advantages over the conventional method of incorporating iron powder in the cathodes and the anodes as the conventional method results in poor electrical performances and raises health concerns, despite its relative straightforwardness. Yet, as the investigations on concrete batteries are still rudimentary, the resulting batteries are inferior compared to their conventional counterparts. Their advantages and disadvantages are listed below.

6.1 Advantages and Disadvantages of the Concrete Battery

6.1.1 Advantages

1. **The concrete battery can be used in multiple situations.** Concrete is one of the most commonly used building materials, as it can be found in apartments, houses, and large infrastructures. A large amount of energy can be stored if a part of the concrete used is replaced by concrete batteries. In comparison, conventional batteries must be stored in limited indoor areas to protect them from the environment. This characteristic of conventional batteries makes them impracticable in most non-ideal situations and thus, they are less practicable than concrete batteries.

2. **Using concrete batteries saves space.** Many batteries are too large to be employed by homeowners despite the satisfying electrical performance of these large batteries. In other words, the space that batteries take must be small enough to meet the demand of families. Installing concrete batteries is the most efficient way to save space since they can also serve as walls. Families can maximize their space utilization rates by using concrete batteries instead of other batteries that take extra space.

3. **Concrete batteries are effective in large buildings.** Although the energy density of concrete batteries is much lower than that of conventional rechargeable batteries, which means that a small unit volume of concrete batteries cannot store much energy, a large amount of energy can be stored if concrete batteries are used on a large scale. For large buildings with a large volume of walls, concrete battery is an effective method of energy storage. In comparison, the size of the building is irrelevant to the amount of electricity that conventional batteries can store.

4. **Concrete batteries are well protected.** Due to the expected structural strength and the method of storing of concrete batteries, the chance of for concrete batteries to get damaged is low compared to conventional batteries. The main reason is that concrete batteries are usually stored inside the walls with no exposure to the external environment. In contrast, extra protection is indispensable for conventional batteries since they tend to be more sensitive to humidity, external forces and other uncontrollable factors.

6.1.2 Disadvantages

1. **Concrete batteries have low energy densities.** The energy density of the concrete battery is $0.8Wh/L$, which is much lower than that of a conventional rechargeable battery. Thus, compared to other batteries, the same volume of concrete battery is inefficient in storing energy. Although the total capacity would be sufficient for large buildings, some small houses would not be able to use concrete batteries due to this limitation.

2. **Maintaining the concrete batteries is difficult.** The expected maintenance difficulty of concrete is much larger than that of other normal batteries. For conventional batteries, the only thing that owners have to is to replace old batteries with new ones. However, in order to repair and replace the concrete batteries, homeowners need to dismantle the walls consisting the batteries. As a result, the installation and maintenance costs are expected to be much higher than those of conventional batteries.
3. **Concrete Batteries have unstable output voltages.** According to Emma Qinguan Zhang and Luping Tang's experiments, the reaction mechanisms of the concrete batteries change during the process of discharge[21]. Consequently, the voltage changes unexpectedly at certain points. Some appliances may not operate normally due to this change. Thus, it is unsuitable for a family to fully rely on concrete batteries.

6.2 Potential Usages

After analyzing the usability of concrete batteries, we concluded that, due to the low development level of concrete batteries, it is currently unsuitable for families to heavily rely on this type of energy storage. Yet, the characteristics of concrete batteries can be fully exploited if they are only used in emergencies.

According to Emma Qinguan Zhang and Luping Tang's experiments, the energy density decreases greatly after a few cycles of discharge[21]. As a result of this disadvantage, concrete batteries should not be used on a daily basis. In the experiments, the energy density shows a clear decreasing trend from $7.10Wh/m^2$ in the first discharging cycle to $6.11Wh/m^2$ in the sixth cycle. Instead of using concrete batteries on a daily basis, energy should be stored in them for long terms and used when the energy in stored in conventional batteries are depleted under rare extreme conditions.

Furthermore, the capacity of these batteries is limited, which means that the energy stored may not be sufficient to support all of the electrical appliances in a house. The energy density of the concrete battery is $0.8Wh/L$, which is much lower than the average value for conventional batteries of $550Wh/L$. Although the total volume of concrete battery is large, the total energy storage would still be inefficient to support a family with a small house. The role of concrete batteries is to make sure that people can live under emergencies. In other words, concrete batteries should only be expected to support necessary appliances.

In addition, due to the unstable voltage provided by the batteries, some appliances may not operate properly if concrete batteries are used to support all the appliances.

6.3 Additional Information Required for the BRM

In order to compare the practicability of concrete batteries with other batteries, the information provided in the essay is insufficient to make a solid conclusion. There are some categories of data that must be obtained to make the comparison valid and establish a comprehensive image of the practicability of the concrete batteries. The categories of the data needed are listed below.

1. **Structural Strength:** Unlike conventional batteries, which are placed stably with limited forces exerted on them, concrete batteries are parts of the structure of the buildings. Besides storing energy, concrete batteries also need enough structural strength to physically support the house. According to the study[21], a small proportion of water, which may lower the structural strength, is needed to construct the concrete batteries. Experiments must be done to ensure that concrete batteries are strong enough to withstand extreme structural strains.
2. **Energy density:** According to the six experiments mentioned in the essay, the concrete battery's energy density decreases in every discharge cycle. The uncertainty of this trend makes concrete batteries impracticable. More experiments must be done to examine whether the value of energy density will approach a constant value or continue to decrease with every cycle. The concrete batteries would be more practicable if evidence shows that the energy density is constant after several discharge cycles.

3. **Price:** In order to compare the practicability of concrete catteries with other batteries, the cost of production and the price of the products must be considered. If the cost of installation is too high, this method is impracticable regardless of the high quality of the batteries. On the other hand, batteries can still be suitable even if other factors are all unsatisfying while the price is low. Consumers can buy several affordable batteries to reach their goals. The authors of the study mentioned that the materials are 'commercially available'[21]. However, in order to compare the practicability of concrete batteries with that of other conventional batteries, numerical data is needed.

4. **Continuous Power:** The value of the continuous power is not given in the essay. This data is needed to determine the number of different types of appliances the concrete batteries can support. If a concrete battery can provide sufficient amount of energy to support a household, then it can be used solely. However, if the continuous power concrete batteries are capable producing is lower than the sum of the power required for appliances that would be used simultaneously, permanent and irreversible damages would be caused, resulting in decreasing battery lifetimes.

5. **The Volume of the Concrete Structure of a Building:** Unlike conventional batteries, concrete batteries are installed within walls. Thus, the total capacity is determined by the volume of the walls. If the total volume of the walls is large, installing concrete batteries would be an effective choice. On the other hand, if the total volume of the walls is too small, concrete batteries would not have the capacity to support a family.

7 Conclusion

In conclusion, the BRM model has some strengths that increase its practicability and weaknesses that limit its accuracy.

7.1 Strengths

1. Consumers' different situations and preferences are fully considered. Beside the data regarding electrical appliances, consumers' objective preferences are also indispensable parts of the calculation. It is very likely that consumers can find the most suitable batteries that satisfy most of their needs with this model as multiple questions are asked to clarify their requirements.

2. Multiple types of batteries are considered. Different types of batteries have various advantages that make them suitable for different needs. In this model, battery types such as NMC, LFP, LTO, SLA and GEL are examples of the candidates that may match with consumers' demands.

3. Factors that may influence the capacity of the batteries are considered comprehensively. Characteristics including the usable capacity, the efficiency of batteries and capacity fade resulting from degradation are taken into consideration. Thus, the real amount of power that a battery can produce after getting fully-charged can be determined accurately.

7.2 Weaknesses

1. Compared to those of lithium-based batteries, the capacities and the power rates of acid-based batteries are not accurately reflected due to lack of information: the capacity and the power output for the same acid battery can vary with factors such as discharging times. As such values of acid-based batteries vary widely, the average value is used during calculations, resulting in potential uncertainties.

2. The effect of temperature on the properties of batteries is neglected. In some extreme environments, the efficiency of batteries may be affected. Since the atmospheric temperature usually stays in the range in which batteries can operate properly, the effects of changing temperatures are not considered.

3. The cost of the solar panels required to charge the chosen batteries and the efficiency and the costs of additional devices such as inverters are neglected to simplify the model. The models focus on choosing batteries alone.

8 One-Page News Article

Scientists Reveal the Battery's New Hope

By Team # 11931

Nowadays, with the development of technology, consumers' need for electricity increases. Resulting from the rise in social awareness of the importance of clean energy sources, a skyrocketing number of families are trying to use solar energy to meet their daily energy needs. Due to the large demand of installing solar panels and rechargeable batteries, a model that assists consumers to choose the most suitable battery is essential. With the assistance of this model, named the BRM, consumers can obtain a list of batteries of different types that correspond to their demands.

The model matches the properties of the batteries with the requirements of consumers. The categories of data that consumers must enter to maximize the accuracy of the results include information about the electrical appliances, which consists of each appliance's power, working period, the level of benefits that it can bring and the its necessity. The model can then determine the daily total energy, the daily necessary energy, and the peak power rate of a household. Furthermore, consumer's personal preferences are considered. For example, factors such as budget, expected lifetime of the batteries, maintenance intervals, expected dimensions of the batteries and safety requirements should be entered in addition to the information regarding electrical appliances. Last but not least, consumers have the right to decide which factors are more important.

Figure 3: Solar panels can now be seen on rooftops.[22]

Lithium-based battery and acid-based battery are currently the two main types of commercially available batteries. Compared to acid-based batteries, lithium-based batteries usually have larger capacities and power rates. However, although lithium-based batteries tend to have satisfying qualities, their prices are always higher than those of acid-based batteries. Yet, of recently-invented battery that have great potentials in the near future — the concrete battery - may offer a new hope.

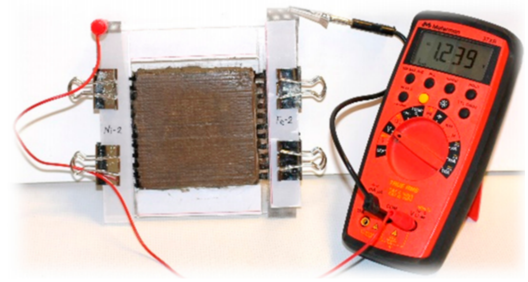

Figure 4: Scientists are still working on the development of preliminary concrete batteries.[21]

Since the concept of 'concrete batteries' is proposed this year, investigators did not have sufficient time to develop this technology and make it practicable. So far, scientists have proven that this technology is theoretically feasible. Their conclusion is supported by basic experiments. Currently, due to the limitation of the scale of the experiments, the practicability of this type of energy source is still unknown. Experts state that there is no doubt that this technology will become fully-developed and that it will benefit humanity. Some scientists anticipate that concrete batteries will replace both lithium-based batteries and acid-based batteries and become the most efficient electricity storage method. Furthermore, concrete batteries can be used to build parts of large buildings and infrastructures. Thus, the space inside the walls can be fully exploited, and the space that are originally used to store batteries can be conserved and used for other purposes.

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