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Research on off-the-grid energy storage system

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Abstract. To enable people in remote areas to meet their energy needs during cloudy days or at night, our team decided to tailor an off-the-grid energy storage system for them. To allow this energy storage system to meet the energy usage of a 1,600-square-foot family, we comprehensively consider the factors about continuous power rating, instantaneous power rating, usable capacity, round-trip efficiency, lifetime of battery, and price of batteries to maximize efficiency and lower costs. In the modeling process, the mathematical method we use is the Analytic Hierarchy Process. Verify whether the matrix passes the consistency test by calculating the eigenvalues and eigenvectors of the matrix, and get a score for each battery. Among the five batteries, we found that the battery Deka Solar 8GCC2 6V 198 can best meet our needs. Then, to perfect the model, we added a new consideration, which is personal preference, including all the subjective factors that would affect people's choice. After incorporating this new consideration into our original model, the rankings of two of the five batteries have changed. However, despite these slight swifts, battery Deka Solar 8GCC2 6V 198 is still our best choice. Nowadays, researchers have discovered some new types of batteries to store energy, such as cement batteries, and this new type of battery has some unique advantages. We compare currently available batteries with the cement batteries, and discover that both batteries have their pros and cons. We believe that with the development of technology, cement batteries will have a very broad prospect and can even surpass currently available batteries.

Keywords: AHP, Impact factor, Off-the-grid energy, Geometric method.

1. Background

Our team is helping the 1600-square-foot homes in remote areas to choose batteries suitable for them to implement an off-the-grid energy storage system. The system could store enough energy and meet the requirements through capturing electricity and store them into other forms of energy. This choice requires consideration of various factors in order to select the best solution, which is able to provide those homes with sufficient energy and can even continue to work on a cloudy day or at night. To solve the power supply problem, our team will choose the most suitable battery from five types. The method we chose is analytic hierarchy process (AHP).

2. Selection of Batteries

Our team is helping to plan the use of solar power to provide electricity to a 1600 square-foot home being built in a remote area. As the house is in a remote area, the cost of connecting to the grid is very expensive, so we decide to go off-the-grid and invest in energy storage. To solve this problem, we did the following work:

(1) To solve the problem 1, we took five batteries and established six factors. Based on AHP, the weight of six factors is compared to establish consistency matrix and carry out consistency test. The final score for each of the five batteries is obtained.

(2) To solve the problem 2, we added a new factor -- personal preference to make our model satisfy personal preference. Then based on the analytic hierarchy process, we got new scores for five batteries.

(3) To solve the problem 3, we compared cement and lithium batteries, analyzed their advantages and disadvantages, and gave a general introduction to their application scenarios.

(4) To solve the problem 4, for convenience, we made a one-page non-technical news article of our research content and results.

Finally, we decided that battery Deka Solar 8GCC2 6V 198 was the best choice.

3. Analytic Hierarchy Process

Analytic Hierarchy Process is a simple method for making decisions on vague problems, and it is especially suitable for problems that are difficult to fully quantitatively analyze. It is a simple, flexible, practical and multi-criteria decision-making method proposed by American operations researcher Professor T. L. Saaty in the early 1970s [1].

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The use of analytic hierarchy process modeling to solve problems can generally be carried out in the following four steps.
(a) First, establish a hierarchical structure model. When applying AHP to analyze decision-making problems, the problem must be organized and hierarchized first, and a hierarchical structural model must be constructed. These levels can be divided into three categories: the highest level (target level), the middle level (criteria level), and the lowest level (program level). The number of layers in the hierarchical structure is related to the complexity of the problem and the level of details that need to be analyzed. Generally, the number of layers is not limited. There are generally no more than 9 elements dominated by each element in each level.
(b) Second, construct all judgment matrices in each level. Each criterion in the criterion layer does not necessarily have the same weight in the target measurement. In the minds of decision makers, each of them occupies a certain proportion, and the numbers 1-9 and their reciprocals are used as a scale to define the judgment matrix. Different scales represent different importance.
(c) The third is the level list sorting and consistency check. Calculate the consistency index *CI*, and find the consistency index *RI* next. Then, calculate the value of the consistency ratio *CR* by dividing *CI* by *RI*. When $CR<0.10$, it is considered that the consistency of the judgment matrix is acceptable, otherwise, the judgment matrix needs to be appropriately modified.
(d) The final step is to perform hierarchical total ranking and consistency test. Finally, each element, especially the sorting weight of the target in the lowest layer of the scheme, is obtained, and the scheme selection is carried out. In addition, the overall ranking of the hierarchy also needs to be tested for consistency, to calculate the composite weight of the elements of each layer to the total goal of the system, and to sort the selected schemes.
To choose the suitable battery among the five batteries, we refer to a few of the most common decision criteria and establish consistency matrix. Finally, the suitable battery is obtained by consistency sorting. The types of batteries are denoted by *a*, *b*, *c*, *d* and *e*.

4. Symbol Description

a - Deka Solar 8GCC2 6V 198
b - Trojan L-16 -SPRE 6V 415
c - Discover AES 7.4 kWh
d - Electriq PowerPod 2
e - Tesla Powerwall+
F_1 - continuous power rating
F_2 - instantaneous power rating
F_3 - usable capacity
F_4 - round-trip efficiency
F_5 - lifetime of battery
F_6 - price of batteries
F_7 - personal preference

5. Solution of problem 1

5.1 Mathematic model

According to the official statistics, the average number of people per family in the United States in the last ten years is between 3.12 and 3.18 [2]. So, there are approximately three people in one typical family. Thus, we can assume that three people in this home will be using energy. Energy is indispensable in people’s daily life at home, and almost everything in the home need energy including items such as heating, hair dryers, washers, air conditioners, ovens, etc. [3]. Different items need different levels of energy, and the Table 1 shows some of their respective energy requirements.

Table 1. Energy requirements

Number	Types of items	Energy requirements
1	Heating [4]	1.5 kilowatts per hour
2	Hair dryer	1.2 kilowatts per hour
3	Clothes washing machine	Between 2.3 kWh per load and 6.3 kWh
4	Air conditioner	Between 2,000-4,000 watts or .2556 kWh or .5132 kWh
5	Oven [5]	2.3 kWh

However, people don't use electrical appliances at home all the time of day. The traditional American business hours are 9:00 a.m. to 5:00 p.m., Monday to Friday [6], and a new report released by the U.S. Census Bureau in 2021 shows the average one-way commute in the United States increased to a new high of 27.6 minutes in 2019 [7]. So, people probably stay at home only from 5:30 p.m. to 7:30 a.m. every weekday. And during this period of time, they will use energy in the home.
There are several important factors to consider when deciding the "best" battery storage system, and we list six considerations as shown in the Table 2 below, using F_1, F_2, F_3, F_4, F_5 and F_6 to represent them separately.

Table 2. Factors of choice

Number	Name	Symbol
1	Continuous power rating	F_1
2	Instantaneous power rating	F_2
3	Usable capacity	F_3
4	Round-trip efficiency	F_4
5	Lifetime of battery	F_5
6	Price of batteries	F_6

By comparing the relative importance of different factors, we determine the weight of each factor. When the two factors are compared, there are different scales to show their relative importance, which is shown in the Table 3 below.

Table 3. Different scales

Scale	Importance
1	The two factors are equally important
3	one factor is slightly more important than the other
5	one factor is obviously more important than the other factor
7	one factor is strongly more important than the other
9	one factor is extremely more important than the other
2, 4, 6, 8	the two factors are equally important

We set the consistency matrix A formed among the six indicators, showing the relationship between each factor, which is shown below.

$$A=\begin{pmatrix} 1 & 5 & 9 & 3 & 7 & 2 \\ 1/5 & 1 & 7 & 1/3 & 4 & 1/5 \\ 1/9 & 1/7 & 1 & 1/7 & 1/3 & 1/9 \\ 1/3 & 3 & 7 & 1 & 3 & 2 \\ 1/7 & 1/4 & 3 & 1/3 & 1 & 1/5 \\ 1/2 & 5 & 9 & 1/2 & 5 & 1 \end{pmatrix}$$

Where, a_{ij} represents the weight of index j relative to index i.

Our team chooses five types of battery that are available to store energy. They are Deka Solar 8GCC2 6V 198, Trojan L-16 -SPRE 6V 415, Discover AES 7.4 kWh, Electriq PowerPod 2, and Tesla Powerwall+ [8]. We use *a*, *b*, *c*, *d*, and *e* to represent them separately, Table 4 below shows the battery types and their respective symbols.

Table 4. The battery types and their respective symbols

Number	Name	Symbol
1	Deka Solar 8GCC2 6V 198	*a*
2	Trojan L-16 -SPRE 6V 415	*b*
3	Discover AES 7.4 kWh	*c*
4	Electriq PowerPod 2	*d*
5	Tesla Powerwall+	*e*

Next, we set the consistency matrices below to help us analyze how those factors would affect the various types of battery and further determine the efficiency of energy storage of each battery sort.

The consistency matrix formed by various batteries for factor F_1 is shown as B_1.

$$B_1=\begin{pmatrix} 1 & 3 & 7 & 9 & 9 \\ 1/3 & 1 & 3 & 9 & 7 \\ 1/7 & 1/3 & 1 & 7 & 5 \\ 1/9 & 1/9 & 1/7 & 1 & 3 \\ 1/9 & 1/7 & 1/5 & 1/3 & 1 \end{pmatrix}$$

The consistency matrix formed by various batteries for factor F_2 is shown as B_2.

$$B_2=\begin{pmatrix} 1 & 1/3 & 9 & 5 & 7 \\ 3 & 1 & 7 & 4 & 5 \\ 1/9 & 1/7 & 1 & 3 & 5 \\ 1/5 & 1/4 & 1/3 & 1 & 3 \\ 1/7 & 1/5 & 1/5 & 1/3 & 1 \end{pmatrix}$$

The consistency matrix formed by various batteries for factor F_3 is shown as B_3.

$$B_3=\begin{pmatrix} 1 & 2 & 3 & 5 & 7 \\ 1/2 & 1 & 2 & 3 & 5 \\ 1/3 & 1/2 & 1 & 3 & 6 \\ 1/5 & 1/3 & 1/3 & 1 & 4 \\ 1/7 & 1/5 & 1/6 & 1/4 & 1 \end{pmatrix}$$

The consistency matrix formed by various batteries for factor F_4 is shown as B_4.

$$B_4=\begin{pmatrix} 1 & 1 & 7 & 9 & 3 \\ 1 & 1 & 5 & 7 & 2 \\ 1/7 & 1/5 & 1 & 3 & 1/3 \\ 1/9 & 1/7 & 1/3 & 1 & 1/5 \\ 1/3 & 1/2 & 3 & 5 & 1 \end{pmatrix}$$

The consistency matrix formed by various batteries for factor F_5 is shown as B_5.

$$B_5=\begin{pmatrix} 1 & 1/3 & 5 & 9 & 7 \\ 3 & 1 & 7 & 9 & 9 \\ 1/5 & 1/7 & 1 & 7 & 5 \\ 1/9 & 1/9 & 1/7 & 1 & 1/3 \\ 1/7 & 1/9 & 1/5 & 3 & 1 \end{pmatrix}$$

The consistency matrix formed by various batteries for factor F_6 is shown as B_6.

$$B_6=\begin{pmatrix} 1 & 1/4 & 1/5 & 1/9 & 1/7 \\ 4 & 1 & 1/3 & 1/7 & 1/5 \\ 5 & 3 & 1 & 1/5 & 1/3 \\ 9 & 7 & 5 & 1 & 2 \\ 7 & 5 & 3 & 1/2 & 1 \end{pmatrix}$$

5.2 Model Test

The setting of data standards has a lot of subjectivity, to make the model more perfect, we decide to check the consistency. We judge whether the matrix is a consistent matrix by judging whether the largest eigenvalue λ_{max} of the matrix is equal to n. The more λ_{max} is larger than n, the more serious the degree of inconsistent rows of the matrix. Then, we check the consistency of the judgment matrix as follows. First, we calculate the consistency index *CI*, in which

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{1}$$

Second, we find the corresponding average random consistency index *RI*. For n = 1, 2, 3, 4, 5, 6, 7, 8, and 9. The value of *RI* given by Saaty is shown in Table 5.

Table 5. Value of *RI*

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The value of *RI* is obtained by using a random method to construct 500 sample matrices: randomly from 1 to 9 and its inverse. Then, extract numbers from the numbers to construct a reciprocal matrix, finding the average value of the largest eigenvalue max λ_{max}', and define it.

Third, we calculate the consistency ratio *CR*, in which

$$CR=\frac{CI}{RI} \tag{2}$$

When CR <0.10, the consistency of the judgment matrix is considered acceptable, otherwise the judgment matrix should be modified appropriately to adjust.

Next, we write a program to check the consistency of the matrix by MATLAB. After checking, we find that CR_A= 0.0858, CR_1= 0.1221, CR_2= 0.1912, CR_3= 0.0462, CR_4= 0.0223, CR_5= 0.1222, and CR_6= 0.0555. We notice that matrices A, B_3, B_4, and B_6 are acceptable because the CR is less than 0.10. However, matrices B_1, B_2, and B_5 are not so perfect because the CR of them are greater than 0.10, which are not quite acceptable so that we need to modify the matrices, and the Table 6 below shows our testing results.

Table 6. Testing results

Matrix	*CR*	Acceptable/unacceptable
A	0.0858	acceptable
B_1	0.1221	unacceptable
B_2	0.1912	unacceptable
B_3	0.0462	acceptable
B_4	0.0223	acceptable
B_5	0.1222	unacceptable
B_6	0.0555	acceptable

5.3 Model Modification

Since there are three out of seven matrices are imperfect, we have to modify them. We use the geometric average method to calculate the feature vector. First, we multiply the vectors in each row and turn it into a 5*1 matrix. Next, we take every entry in this new matrix to the fifth power. Add up these five entries to be m, and use the five vectors to divide m separately, which we mark these five numbers as w_1, w_2, w_3, w_4, and w_5. We construct the consistency matrix W as follows:

$$W = \begin{pmatrix} 1 & w_1/w_2 & w_1/w_3 & w_1/w_4 & w_1/w_5 \\ w_2/w_1 & 1 & w_2/w_3 & w_2/w_4 & w_2/w_5 \\ w_3/w_1 & w_3/w_2 & 1 & w_3/w_4 & w_3/w_5 \\ w_4/w_1 & w_4/w_2 & w_4/w_3 & 1 & w_4/w_5 \\ w_5/w_1 & w_5/w_2 & w_5/w_3 & w_5/w_4 & 1 \end{pmatrix}$$

Calculate the disturbance matrix as follows:

$$D = A - W = \begin{pmatrix} 0 & a_{12}-\frac{w_1}{w_2} & a_{13}-\frac{w_1}{w_3} & a_{14}-\frac{w_1}{w_4} & a_{15}-\frac{w_1}{w_5} \\ a_{21}-\frac{w_2}{w_1} & 0 & a_{23}-\frac{w_2}{w_3} & a_{24}-\frac{w_2}{w_4} & a_{25}-\frac{w_2}{w_5} \\ a_{31}-\frac{w_3}{w_1} & a_{32}-\frac{w_3}{w_2} & 0 & a_{34}-\frac{w_3}{w_4} & a_{35}-\frac{w_3}{w_5} \\ a_{41}-\frac{w_4}{w_1} & a_{42}-\frac{w_4}{w_2} & a_{43}-\frac{w_4}{w_3} & 0 & a_{45}-\frac{w_4}{w_5} \\ a_{51}-\frac{w_5}{w_1} & a_{52}-\frac{w_5}{w_2} & a_{53}-\frac{w_5}{w_3} & a_{54}-\frac{w_5}{w_4} & 0 \end{pmatrix}$$

Where $d_{ij}=a_{ij}-\frac{wi}{wj}$.

We sort the absolute values of non-diagonal elements $|d_{ij}|$ from largest to smallest, getting the sort result $\{I_1, I_2, \ldots\}$. We adjust the element value a corresponding to I_s, where s=1, 2,…

(1) If a_{ij}>1 and d_{ij}>0, we decrease the value of a_{ij}, that is a_{ij}-1. If a_{ij}=2, we will not adjust.

(2) If a_{ij}>1 and d_{ij}<0, we increase the value of a_{ij}, that is a_{ij}+1. If a_{ij}=9, no adjustment to be made.

Given the general method above, we substitute the matrices B_1, B_2, and B_5 into it to adjust. After several attempts to adjust, we finally decided to adjust the element $B1_{13}$ of matrix B_1 from 7 to 3, and accordingly, the element $B1_{31}$ is changed from 1/7 to 1/3. Then, the consistency ratio of matrix B_1 could be 0.0971 now, which is acceptable. Similarly, using the method mentioned from above, we finally adjust six elements in the matrix B_2. $B2_{13}$ is changed from 9 to 1, along with the change of $B2_{31}$ from 1/9 to 1; $B2_{14}$ is changed from 5 to 2, along with the change of $B2_{41}$ from 1/5 to 1/2; $B2_{15}$ is changed from 7 to 6, along with the change of $B2_{51}$ from 1/7 to 1/6. After these adjustments, now the matrix B_2 has a consistency ratio of 0.0996 which is less than 0.10 and is acceptable. Finally, we started to improve the matrix B_5, and through several trials, we made the following changes. $B5_{15}$ is adjusted from 7 to 6 and E_{51} changed from 1/7 to 1/6; $B5_{23}$ is adjusted from 7 to 3 and $B5_{32}$ is changed from 1/7 to 1/3; $B5_{34}$ is adjusted from 7 to 4 and $B5_{43}$ is changed from 1/7 to 1/4. Accordingly, the consistency ratio of matrix B_5 became 0.0997 which is within the standard range because it is less than 0.10, and the modifying vectors are shown in the Table 7 below.

Table 7. Modifying vectors

Matrix	Element	Value before the change	Value after the change	*CR* before the change	*CR* after the change
B_1	b_{13}	7	3	0.1221	0.0971
B_1	b_{31}	1/7	1/3		
B_2	b_{13}	9	1	0.1912	0.0996
B_2	b_{31}	1/9	1		
B_2	b_{14}	5	2		
B_2	b_{41}	1/5	1/2		
B_2	b_{15}	7	6		
B_2	b_{51}	1/7	1/6		
B_5	b_{15}	7	6	0.1222	0.0997
B_5	b_{51}	1/7	1/6		
B_5	b_{23}	7	3		
B_5	b_{32}	1/7	1/3		
B_5	b_{34}	7	4		
B_5	b_{43}	1/7	1/4		

With these minor adjustments, all the seven matrices passed the consistency test. We rewrite the modified matrices B_1', B_2', and B_5' as shown below.

$$B_1' = \begin{pmatrix} 1 & 3 & 3 & 9 & 9 \\ 1/3 & 1 & 3 & 9 & 7 \\ 1/3 & 1/3 & 1 & 7 & 5 \\ 1/9 & 1/9 & 1/7 & 1 & 3 \\ 1/9 & 1/7 & 1/5 & 1/3 & 1 \end{pmatrix}$$

$$B_2' = \begin{pmatrix} 1 & 1/3 & 1 & 2 & 6 \\ 3 & 1 & 7 & 4 & 5 \\ 1 & 1/7 & 1 & 3 & 5 \\ 1/2 & 1/4 & 1/3 & 1 & 3 \\ 1/6 & 1/5 & 1/5 & 1/3 & 1 \end{pmatrix}$$

$$B_5' = \begin{pmatrix} 1 & 1/3 & 5 & 9 & 6 \\ 3 & 1 & 3 & 9 & 9 \\ 1/5 & 1/3 & 1 & 4 & 5 \\ 1/9 & 1/9 & 1/4 & 1 & 1/3 \\ 1/6 & 1/9 & 1/5 & 3 & 1 \end{pmatrix}$$

5.4 Model Solving

After adjustment, we began to score the five types of selected batteries. The eigenvectors of matrices A, B_1, B_2, B_3, B_4, B_5, B_6 and C are shown below.

$$W_A=\begin{pmatrix}0.3876\\0.0996\\0.0234\\0.2149\\0.0483\\0.2262\end{pmatrix}$$

$$W_{B1}=\begin{pmatrix}0.4663\\0.2905\\0.1653\\0.0459\\0.0319\end{pmatrix}$$

$$W_{B2}=\begin{pmatrix}0.1779\\0.5176\\0.1684\\0.0971\\0.0444\end{pmatrix}$$

$$W_{B3}=\begin{pmatrix}0.4289\\0.2526\\0.1864\\0.0927\\0.0395\end{pmatrix}$$

$$W_{B4}=\begin{pmatrix}0.4005\\0.3261\\0.0699\\0.0361\\0.1674\end{pmatrix}$$

$$W_{B5}=\begin{pmatrix}0.3163\\0.4684\\0.1339\\0.0309\\0.0504\end{pmatrix}$$

$$W_{B6}=\begin{pmatrix}0.0325\\0.0706\\0.1331\\0.4769\\0.2868\end{pmatrix}$$

We synthesize the weights of each battery corresponding to the weights of various factors, and calculate their respective total ranking weight as shown in the Table 8 below [1].

Table 8. Total ranking weight

Layer A / Layer B	A_1 a_1	A_2 a_2	... ...	A_m a_m	Total ranking weight of layer B
B_1	b_{11}	b_{12}	...	b_{1m}	$\sum_{j=1}^{m} b_{1j}a_j$
B_2	b_{21}	b_{22}	...	b_{2m}	$\sum_{j=1}^{m} b_{2j}a_j$
...	...	...	...	...	
B_n	b_{n1}	b_{n2}	...	b_{nm}	$\sum_{j=1}^{m} b_{nj}a_j$

We substitute the obtained values into the table and get the results as shown in Table 9.

Table 9. The Value of each battery

criterion		F_1	F_2	F_3	F_4	F_5	F_6	Total ranking weight
Weight of criterion		0.3876	0.0996	0.0234	0.2149	0.0483	0.2262	
Weight of battery for each criteria	*a*	0.4663	0.1779	0.4289	0.4005	0.3163	0.0325	0.3170
	b	0.2905	0.5176	0.2526	0.3261	0.4684	0.0706	0.2768
	c	0.1653	0.1684	0.1864	0.0699	0.1339	0.1331	0.1368
	d	0.0459	0.0971	0.0927	0.0361	0.0309	0.4769	0.1486
	e	0.0319	0.0444	0.0395	0.1674	0.0504	0.2868	0.1210

We find that the total scores of the five batteries *a*, *b*, *c*, *d*, and *e* are 0.3170, 0.2768, 0.1368, 0.1468, and 0.1210. According to the comprehensive consideration of selection factors, the order of batteries from good to bad is $a > b > d > c > e$. That is, in consideration of the six factors related to the efficiency of energy storage system such as continuous power rating, instantaneous power rating, usable capacity, round-trip efficiency, lifetime of battery, and cost, we found that the battery Deka Solar 8GCC2 6V 198 is the best, the battery Trojan L-16 -SPRE 6V 415 is relatively good, the battery Electriq PowerPod 2 is at medium level, the battery Discover AES 7.4 kWh is relatively inefficient, and the battery Tesla Powerwall+ is the worst. The Table 10 below shows their order.

Table 10. The order of batteries

Order	Symbol	Name of battery	score	meaning
1	*a*	Deka Solar 8GCC2 6V 198	0.3170	best
2	*b*	Trojan L-16 - SPRE 6V 415	0.2768	Relative good
3	*d*	Electriq PowerPod 2	0.1468	middle
4	*c*	Discover AES 7.4 kWh	0.1368	Relative inefficient
5	*e*	Tesla Powerwall+	0.1210	worst

Thus, the battery Deka Solar 8GCC2 6V 198 is our most ideal choice to be used in the energy storage system.

6. Solution of problem 2

6.1 Model Improvement

We think that the choice of battery is only considered by the six factors mentioned above, which seems a bit incomplete and not universal. Therefore, we decided to add some personal needs and preferences to our model so that it could be more generalized. Personal preferences include many factors. For example, some people prefer batteries with good-looking shapes, some prefer batteries with smaller sizes, and others may prefer batteries that are more practical. We divide these subjective factors into a separate category for consideration, that is, personal preference, using F_7 to represent it. Then, after incorporating it into our original model, the judgment matrix has been modified to be the following one.

$$A'' = \begin{pmatrix} 1 & 5 & 9 & 3 & 7 & 2 & 4 \\ 1/5 & 1 & 7 & 1/3 & 4 & 1/5 & 1/4 \\ 1/9 & 1/7 & 1 & 1/7 & 1/3 & 1/9 & 1/7 \\ 1/3 & 3 & 7 & 1 & 3 & 2 & 1/3 \\ 1/7 & 1/4 & 3 & 1/3 & 1 & 1/5 & 1/5 \\ 1/2 & 5 & 9 & 1/2 & 5 & 1 & 3 \\ 1/4 & 4 & 7 & 3 & 5 & 1/3 & 1 \end{pmatrix}$$

In addition, we have a comparison of the preference between these seven types of batteries, and how this factor would affect the choice for battery is set below in the matrix B_7.

$$B_7 = \begin{pmatrix} 1 & 1/3 & 1/7 & 1/5 & 1/9 \\ 3 & 1 & 1/5 & 1/3 & 1/7 \\ 7 & 5 & 1 & 3 & 1/3 \\ 5 & 3 & 1/3 & 1 & 1/5 \\ 9 & 7 & 3 & 5 & 1 \end{pmatrix}$$

6.2 Model Test

After establishing the modified model, we need to check the consistency, and the steps are the same as mentioned in 3.2. The consistency ratio of matrix A'' is 0.1142, which is larger than 0.10, so we need to adjust it. The consistency ratio of matrix B_7 is 0.0530, which is smaller than 0.10, so there is no adjustment for it. The Table 11 below shows our testing result.

Table 11. Testing Results

Matrix	*CR*	Acceptable/unacceptable
A''	0.1142	acceptable
B_7	0.0530	unacceptable

6.3 Model Modification

There is only one matrix for us to adjust, which is A'', and the steps of adjusting are the same as mentioned in 3.3. After several trials, we decided to make the following changes. We changed a''_{23} from 7 to 3, along with the adjustment of a''_{32} from 1/7 to 1/3; we also changed a''_{25} from 4 to 3, along with the adjustment of a''_{52} from 1/4 to 1/3. After the adjustment, the consistency ratio of matrix A'' dropped to 0.0945, which is quite acceptable. The modifying vectors are shown in the Table 12 below.

Table 12. Modifying vectors

Matrix	Element	Value before the change	Value after the change	*CR* before the change	*CR* after the change
A''	a''_{23}	7	3	0.1142	0.0945
A''	a''_{32}	1/7	1/3		
A''	a''_{25}	4	3		
A''	a''_{52}	1/4	1/3		

6.4 Model Solving

After these modifications, we start to again score the five types of selected batteries. We first list the new feature vectors as below so that we can see more clearly.

$$W_{A''} = \begin{pmatrix} 0.3440 \\ 0.0568 \\ 0.0208 \\ 0.1525 \\ 0.0384 \\ 0.2172 \\ 0.1747 \end{pmatrix}$$

$$W_{B1} = \begin{pmatrix} 0.4663 \\ 0.2905 \\ 0.1653 \\ 0.0459 \\ 0.0319 \end{pmatrix}$$

$$W_{B2} = \begin{pmatrix} 0.1779 \\ 0.5176 \\ 0.1684 \\ 0.0971 \\ 0.0444 \end{pmatrix}$$

$$W_{B3} = \begin{pmatrix} 0.4289 \\ 0.2526 \\ 0.1864 \\ 0.0927 \\ 0.0395 \end{pmatrix}$$

$$W_{B4}=\begin{pmatrix}0.4005\\0.3261\\0.0699\\0.0361\\0.1674\end{pmatrix}$$

$$W_{B5}=\begin{pmatrix}0.3163\\0.4684\\0.1339\\0.0309\\0.0504\end{pmatrix}$$

$$W_{B6}=\begin{pmatrix}0.0325\\0.0706\\0.1331\\0.4769\\0.2868\end{pmatrix}$$

$$W_{B7}=\begin{pmatrix}0.0333\\0.0634\\0.2615\\0.1290\\0.5128\end{pmatrix}$$

Then, the total scores of the five batteries *a*, *b*, *c*, *d*, and *e* are 0.2653, 0.2284, 0.1601, 0.1540, and 0.1924, respectively. Since 0.2653 > 0.2284 > 0.1924 > 0.1601 > 0.1540, according to the comprehensive consideration of our selection factors, the order of batteries from good to bad is *a* > *b* > *e* > *c* > *d*. We found that after incorporating the factor of personal preference, the sorting of batteries has undergone slight changes. The first, second, and fourth positions are still a, b, and c, respectively. But the rankings of d and e are swapped. In other words, battery Deka Solar 8GCC2 6V 198 is still the best; battery Trojan L-16 -SPRE 6V 415 is still the relatively good one; battery Discover AES 7.4 kWh is still relatively inefficient. But now battery Tesla Powerwall+ is of the middle level while battery Electriq PowerPod 2 becomes the worst choice. Consequently, we would still consider battery Deka Solar 8GCC2 6V 198 as the best option to suit the energy requirements of a 1,600-suquare-foot family, which is our ultimate choice. The Table 13 below shows the order of the batteries.

Table 13. The order of batteries

Order	Symbol	Name of battery	score	meaning
1	*a*	Deka Solar 8GCC2 6V 198	0.2653	best
2	*b*	Trojan L-16 - SPRE 6V 415	0.2284	Relative good
3	*e*	Tesla Powerwall+	0.1924	middle
4	*c*	Discover AES 7.4 kWh	0.1601	Relative inefficient
5	*d*	Electriq PowerPod 2	0.1540	worst

7. Solution of problem 3

7.1 The Advantages and Disadvantages of Cement Batteries

Cement batteries have a lot of unique advantages compared to traditional batteries such as lithium-ion batteries.

(1) The storage capacity of concrete solutions could be expanded by incorporating them into an entire concrete building. This means that the entire concrete buildings could function as giant cement-based batteries in the future, and the units could supply enough energy to households even on a cloudy day or during winter [9].

(2) Cement batteries can also solve the cost problems because they can play different roles at the same time, serving as both energy storage and building materials, making them a rather cost-effective solution for storing energy compared to traditional ones.

However, each coin has two sides. Although cement batteries overwhelmed the traditional ones in some extents, they still have some shortages.

(1) The density of cement is relatively low, being only at 0.8 Watt hours per liter, which is hundreds of times less energy-dense than a lithium-ion battery, and is completely useless for transportation of electricity [10].

(2) The battery's life might not match the long periods over which concrete structures are expected to last so that how to keep the battery work while the building is still in use is a potential concern to be addressed.

(3) Concrete currently has an immense environmental cost, the production of it generally accounts for 4-8 percent of global carbon emissions which would harm the environment in a large extent.

Figures 1-3 below shows some of the comparisons between cement battery and lithium-ion battery based on the collected data.

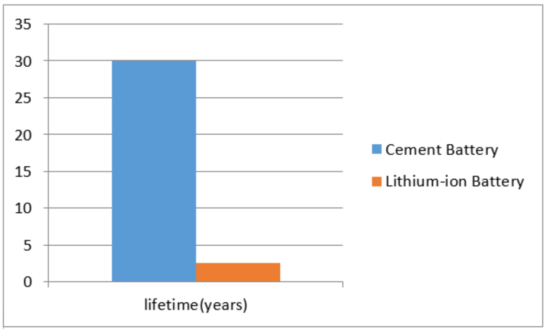

Figure 1. Comparison between lifetime

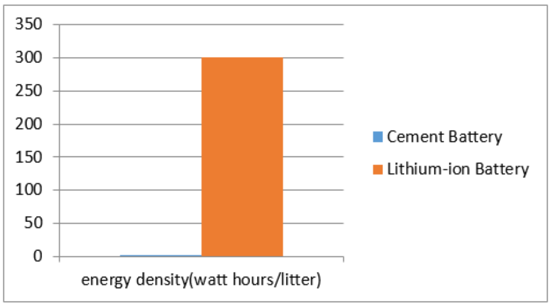

Figure 2. Comparison between energy density

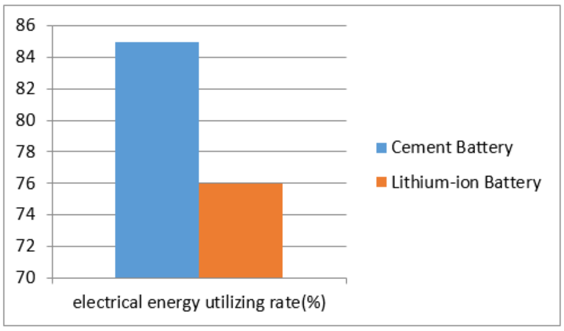

Figure 3. Comparison between electrical utilizing rates

(1) From Figure 1, we could see that the lifetime of cement batteries are nearly 30 years which is longer than that of lithium-ion batteries of 2 to 3 years;
(2) From Figure 2, the energy density of cement batteries is only 0.8 watt hours per litter which is very low, and that of lithium-ion batteries is 250-350 watt hours per litter which is relatively higher [11];
(3) From Figure 3, the electrical energy utilizing rate of cement batteries is slightly higher than that of lithium-ion batteries [12].
I would likely to combine the cement batteries with solar panels such as powering 4G services in remote locations for the off-the-grid homes. Concrete structures such as bridges often need a small amount of electricity for sensing devices or cathodic protection against corrosion of metal, which could fit the cement batteries well. Maybe the whole sections of multi-storey buildings can be made out of concrete, and any concrete surface could have a layer of this electrode embedded. Giant cement batteries can be formed by pouring a cement bucket weighing tens of tons, and we use them to store excess electricity, avoiding energy waste. When electricity is needed, we can use the crane to drop the cement from high altitude, and let the gravitational potential energy transform to drive the generator to operate, thereby generating electricity [13].

7.2 Additional information to compare

Because we have considered the seven factors of continuous power rating, instantaneous power rating, usable capacity, round-trip efficiency, lifetime of battery, cost, and personal preference in the previous battery selection process, if we want to additionally compare the performance of cement batteries and currently available batteries, these factors should also be taken into consideration, and all of them are closely related to the efficiency of solar-power storage.

8. Non-technical news article

Overall, we chose five batteries, Deka Solar 8GCC2 6V 198, Trojan L-16 -SPRE 6V 415, Discover AES 7.4 kWh, Electriq PowerPod 2, and Tesla Powerwall+, as options. In order to find the best battery that can meet the electricity demand of a 1600-square-foot home, we set six parameters for reference and modeling. They are continuous power rating, instantaneous power rating, usable capacity, round-trip efficiency, lifetime of battery, and cost. After comprehensive comparison, we found that the battery Deka Solar 8GCC2 6V 198 is the most ideal choice. It can not only meet the electricity needs of households in remote areas, but also has the most comprehensive advantages. Then, in order to make our judgments and choices more general and universal, we added a more subjective factor of personal preference into consideration. Ultimately, after careful analysis and researches, we found that the battery Deka Solar 8GCC2 6V 198 is still the best and most suitable one, so we finally determined our choice. After that, we made a comprehensive comparison between the traditional lithium-ion battery and the new cement battery. We discovered that although the cement battery still has some shortcomings and imperfections compared to the lithium-ion battery, some of its advantages are very significant and important such as a very long lifetime. Therefore, we believe that in the near future, with the further development of science and technology and the further improvement of research abilities, cement batteries will have a very broad application prospect, and can help us optimize the energy storage system, as well as extending the time of usage. In terms of both space and time, it will brought a qualitative leap for us, and our team strongly recommend people to try this kind of cement battery which will definitely satisfy their energy requirements very well.

9. Conclusion

This article uses the analytic hierarchy process to solve the problem of battery selection, and ultimately we successfully find out a method that can provide suitable power supply for 1600-square-foot households in remote areas. The specific conclusions are as follows.
(1) Among the five types of batteries, Deka Solar 8GCC2 6V 198, Trojan L-16 -SPRE 6V 415, Discover AES 7.4 kWh, Electriq PowerPod 2, and Tesla Powerwall+, battery Deka Solar 8GCC2 6V 198 is the best option when considering the six objective factors of continuous power rating, instantaneous power rating, usable capacity, round-trip efficiency, lifetime of battery, and cost.
(2) After adding the subjective factor of personal preference, battery Deka Solar 8GCC2 6V 198 is still the most suitable choice among all the five kinds of batteries.
(3) Comparing cement batteries with traditional lithium-ion batteries, we find that both of them have their pros and cons. Cement batteries have very long lifetime and high electrical energy utilizing rate but very low energy density. While traditional lithium-ion batteries have relatively short life span and low electrical energy utilizing rate, their advantages are their high energy density.
(4) Since the cement battery has many prominent and crucial advantages over the traditional ones, it will definitely replace the old ones and has a broad prospect in the future as the technology develops.

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