Team Control Number

11558

Problem Chosen

A

2021

HiMCM

Summary Sheet

Optimum Battery Model Based on AHP and TOPSIS

Summary

Adoption of solar energy for home usage is becoming increasingly popular nowadays, which has led to an increased demand for solar energy storage systems, and consequently various suppliers of such storage systems. An objective evaluation model, which can address the following four problems, is thus needed to provide trustworthy suggestions of solar energy storage systems to numerous households.

For problem 1, to build the battery system, we first identify the energy needs, which are **power rating** and **total energy required**. After that, we design storage systems to satisfy such energy needs. When evaluating the energy storage systems designed, we translate the battery factors into ratings from 1 to 9, and then use an **analytic hierarchy process** to calculate the relative importance, the weight, of each factor. The **Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) analysis** is thereafter used to find the similarity of each battery storage system respective to the worst situations. This helps us select the best solar energy storage system for the 1600-square-foot off-the-grid home that we are planning to build.

For problem 2, we further generalize our model, enabling it to provide suggestions to every household in need. Firstly, we introduce quantitative models of the factors influencing the energy needs: **size of the house**, **number of family members**, **average temperature**, and **energy consumption habits**. Secondly, we utilize **public surveys** to obtain individual factors that determine personal preferences. Then we evaluate the model's strength and weaknesses.

For problem 3, we survey recent research on cement batteries about the operation principles, properties and both advantages and disadvantages. Then we identify what other data is needed to include cement batteries as an alternative in the model for choosing the best battery storage system.

For problem 4, we explain our solar battery storage decision model and discuss the future of a cement battery through a news article.

Key words: Analytic Hierarchy Process, TOPSIS analysis, Normalization of Factors, Quantitative model, Satisfy Individual Needs, Adaptable to Personal Preference, Comprehension and Detailed Evaluation Model

Contents

1 Introduction

1.1 Background

While most homes situated in urban areas obtain electricity from power companies through power lines day and night, it is extremely expensive for those in remote areas. Hence it is prevalent for people in distant areas to use solar panels as their energy source. One problem that arises is to make sure there is enough energy storage for nights and cloudy days when there's not enough sunlight. Thus people have to choose an appropriate energy storage system.

The energy requirements can vary from different families due to factors like the number of family members and the electrical appliance they use most. And people's preference can also vary in terms of safety, battery life or efforts to maintenance. There are a wide range of batteries available as energy storage systems and they have different capacities, continuous power rating and so on.

Our aim is to build a model to help people select the best option for their energy storage system from a range of batteries with different characteristics. Under the premise that the electrical energy stored by the battery can satisfy households' needs, our model recommends the most suitable battery specific to each family's preference. Without implementing the model, people might take lots of time choosing from a wide range of batteries. This model can definitely have useful applications for saving people's time to decide the best battery.

1.2 Problem Restatement

Based on the background of the problem, to achieve the goal, these 4 problems need to be addressed:

1) a) Identify the factors that determine energy needs for households. Allocate values to each factor for our own home.

b) Determine qualified battery plans to satisfy energy needs and develop a mathematic model to evaluate battery plans in terms of factors like safety and life.

c) Choose the best battery storage system options for our off-grid home using the model we developed

2) Make changes to the model to enable it to offer the best option according to different preferences and energy needs of all households. Explain the effectiveness and limitations of this model.

3) Consider the advantages and disadvantages of using cement batteries to store solar power. Discuss what the ways are to incorporate cement as a battery for our off-grid home. Determine the additional information to build a model and use it to compare the use of cement batteries to currently available batteries for solar power storage system.

4) Present the model in the form of a non-technical news article. Subsequently, give specific examples of implementations of the model and recommendations on the future possibilities of a cement battery.

1.3 Our Work

We give our solutions after mathematically analyzing the problems stated above. The structure of our model is shown in Figure 1.

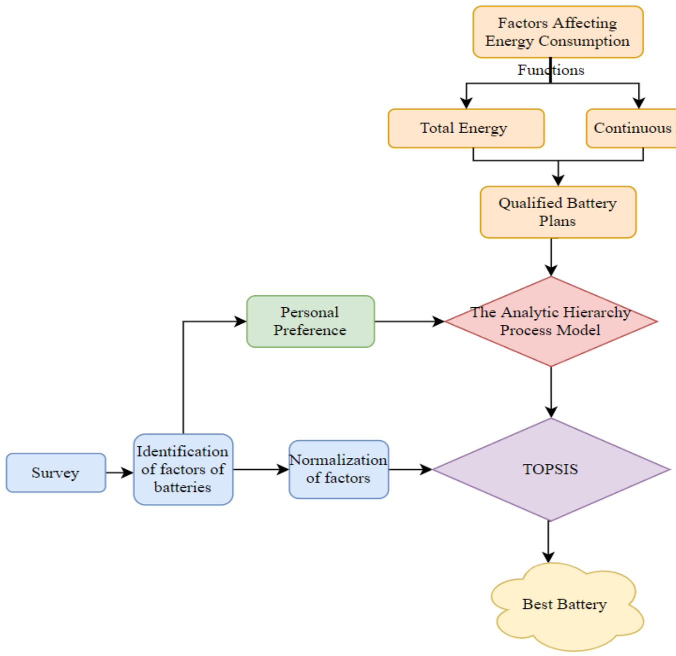


Figure 1: Structure of our work

2 Assumptions

Assumption 1: ***Different types of batteries cannot be connected together.***
Though some different types of batteries with very similar parameters can be used together under strict conditions, most batteries of different types technically cannot. Hence, we assume mixture of different batteries is strictly prohibited.

Assumption 2: ***Households are able to get access to any battery listed.***
It is hard to determine whether the batteries are out of stock or sold in particular regions. We assume households can easily get these batteries as long as they decide to purchase them.

Assumption 3: ***The output power of the solar panel during a cloudy day is negligible.***
It is hard to determine how much energy could be generated during cloudy days and whether it is enough to power the appliances or charge the battery, hence we assume no energy is generated during cloudy days just like at nights.

Assumption 4: ***The energy collected via solar panel is enough to fully charge the battery and supply the energy consumption during daytime.***
Since we do not have any information about the solar panel, such as its size and efficiency, we cannot estimate how much energy could be generated during day time. Hence we assume the energy collected by it during daytime is able to enable normal operation of all appliances and fully charge the battery as well.

Assumption 5: ***No battery has maintenance costs.***
All the batteries listed have a warranty period of at least 10 years, hence we assume

households do not need to pay extra money for maintenance.

3 Notations

Notations	Description
P_{vA}	Power varying with area
E_{vA}	Energy varying with area
E_f	Energy not varying with area
A	Area
N	Population
P_T	Power at temperature T
E_T	Energy at temperate T
T	Temperature
μ	Constant of personal habit
D	Number of days needed for energy use
E_{total}	Total energy needed
$N(x_i)$	Normalized factor ratings
CI	Consistency index
β_i	Weight of factor i
A_w	Set of worst conditions
A_b	Set of best conditions
d_{iw}	Geometric distance to the worst condition
d_{ib}	Geometric distance to the ideal condition
s_{iw}	Similarity to the worst condition
$score_i$	Final score

4 Factors We Should Consider (Problem 1a&1b)

4.1 Factors affecting people's energy need

1) What are the types of electrical appliances used and what is their power?

Type of electrical appliances used in the home plays a major role in deciding energy needs. The higher rating power of those appliances, the more energy consumed. After researching types of electrical appliances, we categorized them into 7 sectors: Space heating, Water heating, Kitchen, Lighting, Electronics, Laundry, and Household goods. Power rating of electrical appliances within the same category can differ as well and the choice of the appliances depends on people's personal habits.

The electrical appliances used in this house is listed in table 2.

2) How big is the house?

Energy consumption needs normally increase with the size of the house. For a larger house, there's often a larger number of appliances and it takes longer to heat up the whole house.

In this case, the home is 1600 square-foot as what's given in the question.

3) How many occupants are there in the home?

Basically, the more people living in a home, the more electricity they require. However, the relationship between electricity requirements and number of households is not directly proportional.

In 2020, the average living space per capita is 971 square feet. For a 1600 square-foot house, we assume it is inhabited by only 1 person.

4) When do people use the maximum amount of electricity throughout the year?

Electricity consumption varies with seasons. The consumption peak occurs in summer and winter when more energy is needed for space heating and cooling. Because we only consider energy needs at nights and cloudy days, energy storage requirements would be largest in winter because temperature under these circumstances drops.

Hence here we consider electricity consumption in winter because we hope the battery can satisfy households' maximum needs.

5) How is the climate?

Households in cold areas tend to use more electricity in winter for space heating. Electricity consumption increases as the average temperature in winter drops.

We assume the average temperature in winter of our home is 5 °C.

6) How long will cloudy days last?

The time length of precipitation affects the energy storage requirement. During rainy days and cloudy days, the solar panel is not able to generate enough energy and has to use stored energy from batteries. Also, during this time, households use more energy for lightning. If the home is located in an area where it remains raining for a couple of days, a battery with larger capacity would be appropriate in order to satisfy energy needs.

In this case, for the 1600 square-foot home, we assume it needs to store energy for 24 hours' usage to prepare for a whole day without sunshine.

7) What are the personal habits of the households?

Beside all the subjective factors that can influence people's electricity consumption, objective habits also matter. People can be thrifty and try their best to save energy cost or consume as much as they wish.

We assume people living in this home has average consumption habits.

4.2 Factors of batteries

4.2.1 Description

After researching, and consulting with professionals about the solar energy storage batteries with the highest purchase rate and recommendation percentage, we have selected 10 batteries for evaluation. Including the 5 batteries given by the question, and 5 more batteries that we added.

To determine other factors that need to be considered during evaluation of the batteries, we have conducted a survey asking for the important characteristics of batteries used for solar storage. We expect the number of answers to be around 150. Subsequently, we will go through all the results, and count the answers. The three other factors with the highest appearing frequency, combined with the original seven factors given by the question, will be the ten factors considered in the Analytical Hierarchy Process.

Index Nuber	Battery	Cost (USD)	Battery Type	Weight (lbs.)	Dimension (L×W×D in inches)	Continuous Power Rating (kW)	Instantaneous Power Rating (kW)	Round-Trip Efficiency (%)	Usable Capacity (kWh)	Battery Life (cycles)	Safety (Peak Heating Rate C/min)
1	Deka Solar 8GCC2 6V 198	368	SGLA	68	10.25 × 7.1 × 10.9	0.017	Not Available	80-85%	1.18		
2	Trojan L-16 - SPRE 6V 415	492	FLA	118	11.7 × 6.9 × 17.6	0.023	Not Available	80-85%	2.5		
3	Discover AES 7.4 kWh 48V	6,478	LFP	192	18.5 × 13.3 × 14.7	6.65	14.4 kW (for 3 sec)	>95%	7.4	3000	3
4	Electriq PowerPod 2 240VAC	13,000	LFP	346	27.5 × 50 × 9	7.6	9 kW (for 60 sec)	96.00%	10	3000	3
5	Tesla Powerwall+ 240VAC	8,500	NMC	343.9	62.8 × 29.7 × 6.3	7	10 kW (10 sec)	90.00%	13.5	1000	60
6	Sonnen ECO 7.5 240VAC	10,990	LFP	447	25.625 × 56.375 × 19	3.6	6 kW (5 sec)	80-85%	8	3000	3
7	Senec Home V3	3,999	LFP	176	46.25 × 20.9 × 16.0	5	8.0 kW (3 sec)	95.00%	4.5	3000	3
8	Varta Pulse 6	5764	NMC	143 (able to hang on the wall)	23.6 × 27.2 × 7.5	2.5	Not Available	98.00%	6.5	1500	60
9	LG Chem Resu series	7500	NMC	220	29.30 x 35.70 x 8.10	5	7.0 kW	95%	9.8	1000	60
10	BYD LVS 4.0	2890	LFP	141	19 x 25.6 x 11.8	3.3	Not Available	≥95%	4	3000	3

Table 1: Types and factors of batteries

4.2.2 Factor description

x_1: Price

The prices of batteries have huge impacts on the selection of batteries. Customers may differ in their income level and hence their sensitivity towards an increase in prices. This factor evaluates the greatest cost of installing an off-grid energy storage system.

x_2: Weight

This factor determines the transportation cost of the batteries, during the battery install and replacement of the batteries. Nevertheless, if there is a problem with the battery, such as corrosion to the terminals, it is then necessary to move the battery and weight is then essential to consider as well.

x_3: Volume

Since we are planning the electricity use of a 1600 square foot area, the volume of the battery has a great impact on the final evaluation. Even if the battery is capable of satisfying all the energy needs, it still cannot be chosen if it takes up to much space of the house, since there is an opportunity cost of making other uses of the space.

x_4: Round-Trip Efficiency

Round-trip efficiency of a solar energy storage battery refers to the percentage of electricity generated from the solar panels that can be retrieved for use from the battery.

x_5: Battery Life

Battery life refers to the number of cycles in electro-mobility applications. It is usually measured using the number of cycles it can support before the remaining capacity reduces to 80% of the initial capacity. Lithium iron phosphate batteries are commonly recognized as having the longest battery life, as they have safer cathode material which provide them higher thermal and chemical stability than other types of batteries.

x_6: Safety Rating

We have found the safety rating of a type of battery is related to the peak heating rate for full cell. The lower the normalized peak heating rate, the higher stability the battery has. For instance, lithium iron phosphate battery, LiFePO_4, has the lowest normalized rate, hence it is the most stable and safest battery type. We use the normalized peak heat rate as an indicator of the safety rating.5 Choosing Solar Energy Storage System (Problem 1b&1c)

5 Choosing the best battery for our 1600 square-foot home

5.1 Satisfying energy requirement

5.1.1 Total energy

Considering answers to all questions listed in 4.1 for our 1600 square-foot home, Table 2 shows categories and details of all electrical appliances used in the house, as well as usage time, power rating and total energy required.

Table 2: Total energy consumption of all appliances

CATEGORY	DETAIL	POWER RATING (kWh/hr)	USAGE TIME (hr)	Total Energy Consumption (kWh)
Space heating	Portable heater	1.5	8	12
Kitchen	Oven	2.3	1	2.3
Kitchen	Broiler, portable	1.5	0.2	0.3
Kitchen	Coffee maker	0.12	0.1	0.012

Kitchen	Dishwasher	1.5	1	1.5
Electronics	TV	0.12	2	0.24
Electronics	Desktop computer	0.06	4	0.24
Electronics	Desktop computer on sleep mod	0.03	20	0.6
Electronics	Laptop	0.05	2	0.1
Lighting	CFL/LED (11 W)	0.01	360	3.6
Laundry	Clothes dryer	3.25	0.75	2.4375
Laundry	Washing machine	2.3	1	2.3
Household Goods	Vacuum cleaner	0.75	0.1	0.075
Household Goods	Hair dryer	1.5	0.2	0.3
Water Heating	Electric water heater	380–500 kWh per month		2.72
Refrigerator/Freezer	ENERGY STAR Refrigerator, 14 cu.	34.5 kWh per month		1.15
Total				29.8745

5.1.2 Continuous power

While it is not reasonable for all appliances in the house to be turned on at the same time, some do operate simultaneously for a considerable time. We select several appliances that operate for a relatively longer time to calculate their total power rating to make sure the battery we select can continuously power these appliance when they operate together.

The selected appliances and their rating is shown in Table 3.

Table 3: Total power of selected appliance

type	space heating	refrigerator	lighting	television	oven	dryer	ps5	total
Power (W)	1500	250	3375	150	4000	3000	350	12625

5.2 Available battery plans

The aggregate energy required to power the whole house for one day is calculated as 29.8745 kWh, which means the capacity of the battery should be at least 29.8745 kWh in order to satisfy energy needs.

For the 10 batteries that we choose, the numbers of each required to have enough capacity are calculated and listed in Table 4.

Table 4: Amount of battery needed for enough capacity

Battery	Deka Solar 8GCC2 6V 198	Trojan L-16 - SPRE 6V 415	Discover AES 7.4 kWh 48V	Electriq PowerPod 2 240VAC	Tesla Powerwall+ 240VAC	Sonnen ECO 7.5 240VAC	Senec Home V3	Varta Pulse 6	LG Chem Resu series	BYD LVS 4.0
Usable Capacity (kWh)	1.18	2.5	7.4	10	13.5	10	4.5	6.5	9.8	4
Amount Needed	26	12	5	3	3	3	7	5	4	8

The total power required to enable selected appliances to operate at the same time is calculated as 12625W, which means the continuous power of the battery should be at least 12625W in order to satisfy energy needs.

For the 10 batteries that we choose, the numbers of each required to have enough continuous power are calculated and listed in Table 5.

Table 5: Amount of battery needed for enough continuous power

Battery	Deka Solar 8GCC2 6V 198	Trojan L-16 - SPRE 6V 415	Discover AES 7.4 kWh 48V	Electriq PowerPod 2 240VAC	Tesla Powerwall+ 240VAC	Sonnen ECO 7.5 240VAC	Senec Home V3	Varta Pulse 6	LG Chem Resu series	BYD LVS 4.0
Continuous Power Rating (kW)	0.017	0.023	6.65	7.6	7	3.6	5	2.5	5	3.3
Amount Needed	743	549	2	2	2	4	3	6	3	4

Since the battery should satisfy both total energy and continuous power, the larger value is chosen for the number of each battery when comparing Table 3 to Table 4. The final available battery plan that satisfy the home's energy needs is listed in Table 6.

Table 6: Final amount of batteries needed

Battery	Deka Solar 8GCC2 6V 198	Trojan L-16 - SPRE 6V 415	Discover AES 7.4 kWh 48V	Electriq PowerPod 2 240VAC	Tesla Powerwall+ 240VAC	Sonnen ECO 7.5 240VAC	Senec Home V3	Varta Pulse 6	LG Chem Resu series	BYD LVS 4.0
Capacity	26	12	5	3	3	3	7	5	4	8
Power	743	549	2	2	2	4	3	6	3	4
Final Amount	743	549	5	3	3	4	7	6	4	8

As shown in the last line of Table 6, 743 Deka Solar 8GCC2 6V 198 batteries or 549 Trojan L-16 -SPRE 6V 415 batteries are required to satisfy energy needs. It is obviously not realistic to have so many batteries in the home since they take up too much space and are hard to install and maintain. Hence, we exclude these two options and only consider remaining 8 options.

5.3 Normalization of batteries' data

After designing energy storage systems that satisfy energy needs, we now need to evaluate each system to determine which system is the most suitable option for our off-grid home. Before we start our evaluation model, it is necessary to normalized our different categories of data with different units into scores within the range of 1 to 9 with 1 representing the worst and 9 representing the best.

5.3.1 Cost

To change the cost of different batteries into scores 1 to 9, we developed a function to express the relation between the cost, x_1, and the scores, N(x_1). Since the higher (5-1) costs of the solar energy storage systems require higher income level and willingness to pay, it is less likely for our team to choose the system. Hence, there is certainly an inverse relationship between the cost and the score. What is more, there exits marginal effects when considering costs. Therefore, we found the shape of the graph is like this function (where k is a constant)

$$y = \frac{k}{1 + x^2} \tag{5-1}$$

The lowest total cost of \$23120 is defined to have a score 9, the highest cost of \$43960 is defined as a score 1. Then by integration and plotting the graph, we found the relationship can be best expressed by arctangent function

$$N(x_1) = -30 \arctan\left(\frac{x_1}{60000}\right) + 20 \tag{5-2}$$

Subsequently, we calculated the scores of the cost of each battery system, by inserting the costs as inputs to this equation, and took one significant figure as the final score. The results are below:

Table 7: Cost scores of batteries

Battery	Amount	Total Cost (USD)	Score
Discover AES 7.4 kWh 48V	5	32390	5
Electriq PowerPod 2 240VAC	3	39000	3
Tesla Powerwall+ 240VAC	3	25500	8
Sonnen ECO 7.5 240VAC	4	43960	1
Senec Home V3	7	27993	7
Varta Pulse 6	6	34584	4
LG Chem Resu series	4	30000	6
BYD LVS 4.0	8	23120	9

5.3.2 Weight, Volume & Round-trip efficiency

These 3 factors have similar characteristics. They are purely quantitative, and do not involve marginal effects. Hence we decided to apply the same normalization method to these 3 factors, their scores are denoted as

$$N(x_i),\ where\ i \in \{2, 3, 4\}$$

Now we use the formula below to process our data directly.

$$N(x_i) = \frac{\{N(x_i)_{max} - N(x_i)_{min}\}(x_i - x_{i_{min}})}{x_{i_{max}} - x_{i_{min}}} + N(x_i)_{min} \tag{5-3}$$

After the data is processed, the results are taken 1 significant number. The final scores of these 3 factors are on the table below:

Table 8: Weight, volume and round-trip efficiency scores of batteries

Battery	Amount	Total Weight	Score	Total Volume	Score	Round-Trip Efficiency	Score
Discover AES 7.4 kWh 48V	5	960	8	18084.68	9	95%	7
Electriq PowerPod 2 240VAC	3	1038	7	37125	7	96.00%	8
Tesla Powerwall+ 240VAC	3	1031.7	8	35251.52	8	90.00%	4
Sonnen ECO 7.5 240VAC	4	1788	1	109790.3	1	85%	1
Senec Home V3	7	1232	6	108262	1	95.00%	7
Varta Pulse 6	6	858	9	28886.4	8	98.00%	9
LG Chem Resu series	4	880	9	33890.72	8	95%	7
BYD LVS 4.0	8	1128	7	45916.16	7	95%	7

5.3.3 Battery life

After researching about the lengths of different battery lives, we used the number of charge cycles until the usable capacity drops to 80% of its original value, to represent the battery life.

We define a battery life able to support more than 1,000 charged cycles to be score 1, whereas a battery life able to support more than 3,000 charged cycles to be score 9. Most batteries have either life length more than 1000 or 3000 life cycles, except the energy storage system consists of six Varta Pulse 6 batteries have a life span more than 1500 cycles. We used the function below to determine the score

$$N(x_i) = \frac{\left\{N(x_i)_{max} - N(x_i)_{min}\right\}\left(x_i - x_{i_{min}}\right)}{x_{i_{max}} - x_{i_{min}}} + N(x_i)_{min} \quad (5\text{-}4)$$

The score is processed and recorded in Table 11.

5.3.4 Safety

We measure an energy storage system's safety rating by its stability when it is experiencing a high temperature, which is measured by the normalized peak heating rate.

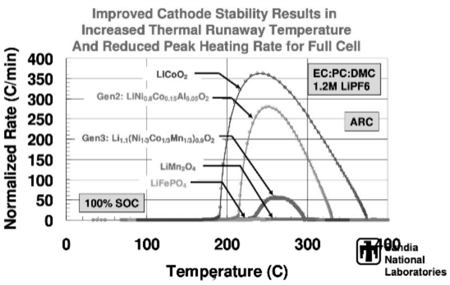


Figure 2: How normalized rate changes with temperature

The lower the normalized peak heating rate, the higher stability the battery has. As shown on the graph, lithium iron phosphate battery, $LiFePO_4$, has the lowest normalized rate, hence it is the most stable and safest battery type. We use the normalized peak heat rate as an indicator of the safety rating.

We define the lowest peak heating rate of 3C/min as score 9, whereas the highest rate of 60C/min as score 1. The scores are shown below:

Table 9: Life and safety scores of batteries

Battery	Battery Life (cycles)	Score	Safety (Peak Heating Rate C/min)	Safety
Discover AES 7.4 kWh 48V	3000	9	3	9
Electriq PowerPod 2 240VAC	3000	9	3	9
Tesla Powerwall+ 240VAC	1000	1	60	1
Sonnen ECO 7.5 240VAC	3000	9	3	9
Senec Home V3	3000	9	3	9
Varta Pulse 6	1500	3	60	1
LG Chem Resu series	1000	1	60	1
BYD LVS 4.0	3000	9	3	9

5.3.5 Final scores table

Table 10: Total scores of batteries

Battery	Cost	Weight	Volume	Round-Trip Efficiency	Battery life	Safety
Discover AES 7.4 kWh 48V	5	8	9	7	9	9
Electriq PowerPod 2 240VAC	3	7	7	8	9	9
Tesla Powerwall+ 240VAC	8	8	8	4	1	1
Sonnen ECO 7.5 240VAC	1	1	1	1	9	9
Senec Home V3	7	6	1	7	9	9
Varta Pulse 6	4	9	8	9	3	1
LG Chem Resu series	6	9	8	7	1	1
BYD LVS 4.0	9	7	7	7	9	9

5.4 Evaluation: Analytic Hierarchy Process

Analytic hierarchy process, also known as AHP, helps people make decision based on multiple criteria, by the 3 sections– goal, criteria, and alternatives in a hierarchy structure. AHP quantifies the criteria and alternative options in a decision-making process and relates these elements to the goal. It works based mainly on linear algebra and calculation of judgement matrix.

In AHP, stakeholders first compare the importance of criteria, two at once, through pair-wise comparisons, to determine the weightage of the criteria. Then numerical priorities are calculated for each of the alternative options. The final decision is made by calculating the total score of each option and rank them to find out the best choice.

The figure given below shows the basic steps in AHP.

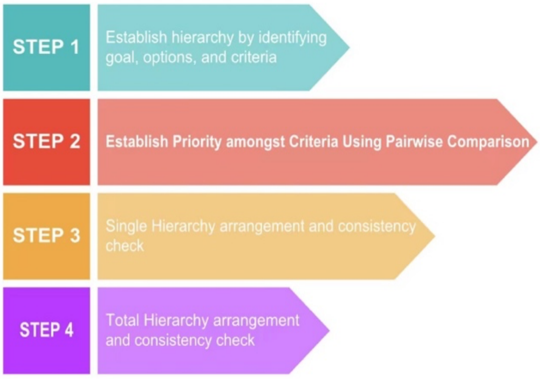


Figure 3: Basic steps in AHP

STEP 1: Establish Hierarchy

Level 1 Overall objective: Solar energy storage system

Level 2 Criteria: Cost, weight, volume, round-trip efficiency, battery life, and safety rating

Level 3 Options: Combinations of batteries

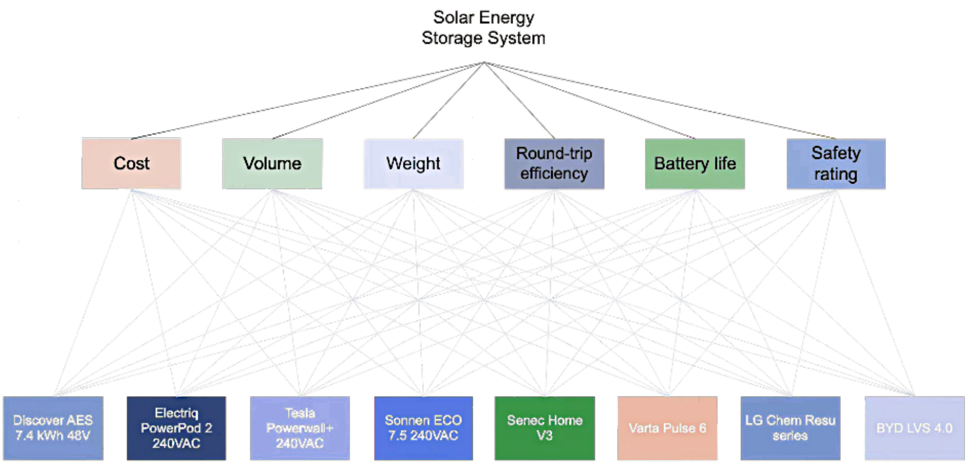


Figure 4: Three levels in AHP

STEP 2: Establish judgement matrix

Now we are going to establish a judgement matrix.

$$[a_{ij}]=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad (5\text{-}5)$$

Constructing this judgement matrix involves:

1) Pair-wise comparisons of the relative importance of factors, instead of comparing all the factors at once. This method first was firstly introduced by T.L. Saaty.
2) Defining a scale of 1-9 with each scale clearly indicating a level of relative importance between the 2 factors. This increases the overall accuracy of the model. The ratings are shown below.

Table 11: Scale and level of importance

Numerical scale	**The level of importance**
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2,4,6,8	Intermediate values between the two adjacent judgements

In this specific research, we will specify the judgement matrix with the house owner and ourselves, as we are responsible for this project.

Table 12: Judgement matrix

	x_1	x_2	x_3	x_4	x_5	x_6
x_1	1	7	7	5	5	5
x_2	1/7	1	1	1/3	1/5	1/5
x_3	1/7	1/7	1	1/3	1/5	1/5
x_4	1/5	3	3	1	2	1/2
x_5	1/5	5	5	1/2	1	2
x_6	1/5	5	5	2	1/2	1

STEP 3: Single hierarchy arrangement and consistency check

A consistent judgement matrix has the following characteristics:

1. $a_{ik} \times a_{kj} = a_{ij}$ (5-6)

2. $a_{ij} = \frac{1}{a_{ij}}$ (5-7)

3. $a_{ij} = 1$, for $i, j = 1, 2, \ldots, n$ (5-8)

An incompatible matrix means it has an incomplete consistency, which makes its credibility unacceptable for further arrangement. Hence, we need to run a consistency check. The consistency index is defined as:

$$CI = \frac{\lambda - n}{n - 1} \quad (5\text{-}9)$$

1. If $CI = 0$, there is perfect consistency.

2. If CI is close to 0, there is sufficient consistency.
3. The larger CI, the larger inconsistency exists.

Next step is to calculate the consistency ratio:

$$CR = \frac{CI}{RI} \quad (5\text{-}10)$$

Random consistency index RI is introduced to measure the consistency ratio:

$$RI = \frac{CI_1 + CI_2 + \ldots + CI_n}{n} \quad (5\text{-}11)$$

Table 16: The values of Random consistency index 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	1.43

It is hold commonly that if the consistency ratio, CR < 0.1, the judgement matrix is within an acceptable inconsistency range. After running the test, we got the value of CR, which is 0.0593, is considered within the acceptable range. This means the matrix passed the consistency test.

After the consistency test, we find out the weight of each factor by using this formula:

$$\beta_i = \frac{a_{ij}}{\sum_{j=1}^{6} a_{ij}} \quad (5\text{-}12)$$

The results are below:

$$w = (0.496 \;\; 0.039 \;\; 0.034 \;\; 0.129 \;\; 0.153 \;\; 0149)$$

5.5 TOPSIS

5.5.1 Introduction of TOPSIS

TOPSIS stands for Technique for Order of Preference by Similarity to Ideal Solution, which is a multi-criteria decision analysis method. This theory of evaluation is firstly proposed by Ching-Lai Hwang and Yoon in 1981, which is based on the belief that the best alternative should have the shortest geometric distance from the ideal situation, and longest geometric distance from the negative ideal situation. We use TOPSIS to help us evaluate the best energy storage system based on their factor ratings' geometric distance from the best alternative.

5.5.2 Calculate the weighted normalized decision matrix

From the sector **5.3**, we already found out the restricted factor ratings of all the batteries. From sector **5.4**, we knew about the weight of each factor from using AHP. Therefore, we multiply them to get the scores of each factor with consideration of the preference of the homeowners and us, as their team to plan the use of solar power of the off-the-grid house. The new matrix R is our data for the next operations.

$$T=[t_{ij}]=[x_{ij}]\cdot W, \quad (5\text{-}13)$$

where $[x_{ij}]$ is the normalized score matrix, W is a diagonal matrix with its diagonal the same value of the weight matrix w

$$w = (0.496\ \ 0.039\ \ 0.034\ \ 0.129\ \ 0.153\ \ 0149)$$

5.5.3 Applying TOPSIS

STEP 1: Determine the worst alternative (A_w), and the best alternative (A_b)

$$A_w = \{<max(r_{ij})|\ j \in J_->, <min(r_{ij})|j \in J_+>\} = \{r_{wj}\} \quad (5\text{-}14)$$

$$A_b = \{<min(r_{ij})|\ j \in J_->, <max(r_{ij})|j \in J_+>\} = \{r_{bj}\} \quad (5\text{-}15)$$

Where $J_+ = \{j = 1,2,\dots,n \mid j\}$ associated with the criteria having a positive impact, and $J_- = \{j = 1,2,\dots,n \mid j\}$ associated with the criteria having a negative impact.

STEP 2: Calculate the L^2-distance between the target alternative i and the two conditions A_w and A_b

The L^2-distance between the target alternative i and the worst condition A_w:

$$d_{iw}=\sqrt{\sum_{j=1}^{n}(t_{ij}-t_{wj})^2}, i=1,2,\dots,8 \quad (5\text{-}16)$$

The L^2-distance between the target alternative i and the best condition A_b:

$$d_{ib}=\sqrt{\sum_{j=1}^{n}(t_{ij}-t_{bj})^2}, i=1,2,\dots,8 \quad (5\text{-}17)$$

where d_{iw} and d_{ib} are L^2-distances from the target alternative i to the worst and best conditions, respectively.

STEP 3: Scores based on the best and worst situations

Calculate the similarity to the worst condition:

$$s_{iw}=\frac{d_{iw}}{(d_{iw}+d_{ib})}, 0\le s_{iw}\le 1, i=1,2,\dots,8 \quad (5\text{-}18)$$

$s_{iw}=1$ if and only if the alternative solution has the best condition.

$s_{iw}=0$ if and only if the alternative solution has the worst condition.

5.5.4 Final ranking of the energy storage systems

After the result is calculated, we use the function below to normalize the final score:

$$Score_i=\frac{s_{iw}}{\sum_{i=1}^{8} s_{iw}}, \text{ where } \sum_i score_i=1 \quad (5\text{-}19)$$

The final results are shown below:

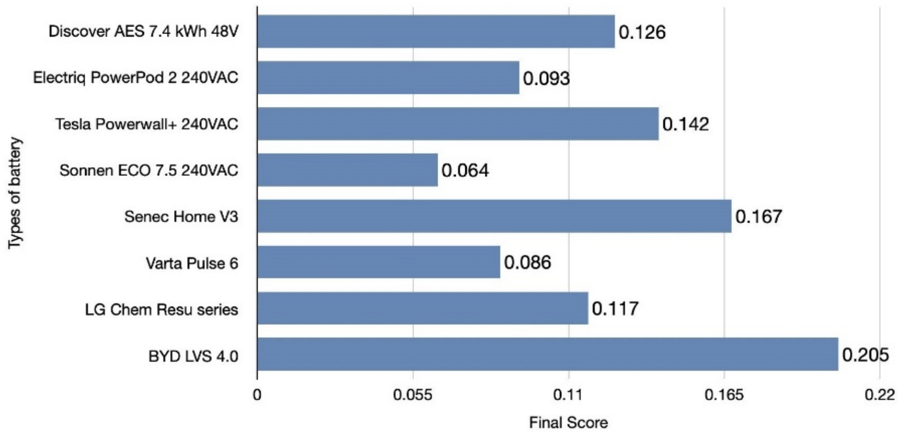


Figure 5: Final result of TOPSIS

Hence, we arrive to our conclusion that BYD LVS 4.0 is the best option for this 1600 square-foot house.

The algorithm used to derive the answers can be found in appendix 9.1.

6 Generalization of model (Problem 2)

To construct a battery system to satisfy individuals' preferences and needs, we still use the method in the basis of sufficient energy storage and power rating, we use AHP to rank the battering systems and find the best choice.

Considering that the conditions and preferences of individuals can be quite different, when we are designing a battery system for the users, we decide to do survey and adjust our model according to individuals' needs instead of giving out an exact form of battery system.

We assume the data we used in question 1 is the "reference situation", hence symbols with subscript 0 represents the value of benchmark given in question 1.

6.1 Determining energy requirements

As explained in 4.1, energy requirements of household can be determined by a range of factors, for instance, number of residents, area of house, weather condition and personal habit.

While energy consumption of some appliances varies with certain factors, some roughly remain unchanged. Hence, we categorize the energy usage into 7 groups, which are Space heating, Water heating, Kitchen, Lighting, Electronics, Laundry, and Household goods.

Among these categories, Space heating and Lighting changes with area of the house while others are roughly constant. Electricity consumed by space heater is proportional to the area of the house. And for Light, the bigger the house is, the more lights it needs. We can assume that the energy usage affected by the house area is proportional to its area. Thus, we have the following Equation:

$$\frac{P_{vA}}{P_{vA0}} = \frac{A}{A_0} \tag{6-1}$$

$$\frac{E_{vA}}{E_{vA0}} = \frac{A}{A_0} \tag{6-2}$$

And for number of occupants, it's obvious that the more people in the house, the more energy they will use for almost every facility. However, they may share the electric usage at the same time, thus the additional energy use is smaller than individual needs, and power rating will not be affected by population badly. Moreover, the more people share the energy use, the more energy they use together. Thus, the derivative of the relationship between the energy usage and number of residents should be a decreasing but positive function. The Equation $\frac{dE_{vN}}{dN} = \frac{1}{x}$ matches the equation. And through integration and plugging in values of (1,1), we estimate the relationship between the energy use varying with population to be:

$$E = [ln(N + 7.03) - 1.20] \times E_0 \tag{6-3}$$

E_0 represents the energy consumption of a single-residence house.

For climate, we ask users for average temperature of the region where the house locates. For extreme temperature, the usage of air conditioner would be increased. And the more extreme the temperature is, the more electricity people tend to use. Thus, the relationship between energy usage and average temperature should approximately be like

$$P_{T_1} = P_{T_0} \times 1.075^{|T_1 - T_0|} \tag{6-4}$$

$$E_{T_1} = E_{T_0} \times 1.075^{|T_1 - T_0|} \tag{6-5}$$

And people have different habits which will also affect the energy usage. This also include the type of appliances that they use. Some people prefer to use appliances with high power while small power is enough for some. We ask users to estimate a percentage to suggest the extent to which they spend electricity. If users think they have average consumption habits, then the percentage should be 100%, if they think they consume as they want, then the percentage should be larger than 100% and vice versa. The energy used should be multiplied by this constant as shown below.

$$P = \mu P_0 \tag{6-6}$$

$$E = \mu E_0 \tag{6-7}$$

To combine these together, we get the following equation to determine the energy used by individual preferences:

$$P = \mu 1.075^{|T_1 - T_0|}(E_{vA0}\frac{A}{A_0} + E_f) \quad (6\text{-}8)$$

$$E = \mu 1.075^{|T_1 - T_0|}[ln(N + 7.03) - 1.20](E_{vA0}\frac{A}{A_0} + E_f) \quad (6\text{-}9)$$

Referring to the " reference situation" in question 1, the variables with subscript 0 have values listed in the form below:

Table 17: Variables and their values

variable	T_0	E_{vA0}	E_f	A_0	D_0
value	5	13.18	16.6945	1600	1

Finally, the least energy capacity necessary of the battery system should be large enough to prepare for the number of days without bright sunshine. Households living in rainy areas should choose batteries with larger capacity in case of contentious rainy days. Hence, we ask users to give number of days D that they need to store energy for according to the weather in their regions.

Then the least energy storage needs for the battery system should be:

$$E_{total} = \frac{D}{D_0} \times E \quad (6\text{-}10)$$

6.2 Determining personal preference

People may have different focus on the characteristics of battery systems, thus it's important as well to investigate their own thoughts. In the AHP model we make for the battery system, the judgement matrix determines the different importance of characteristics. When we are designing a battery system for some specific users, we may ask them to complete the judgement matrix themselves in the progress of comparing two characteristics to get the relative importance, from 1 to 9, in order to form a personal judgement matrix to proceed with the evaluation mode. In this case, personal preferences can be considered in the battery system better.

We designed a survey to get these pieces of information from users, and it's shown in the appendix 9.3.

6.3 Choosing the best battery

Having determined power and energy needs of individuals and personal preferences, the following steps is quite similar to problem 1 and do not require a big change. The algorithm of the model to find the optimum battery is attached in appendix 9.2.

6.4 Evaluation of the model

6.4.1 Strength

1. The sensitivity test proves that the model is credible and stable. As shown by the results, the model has a high sensitivity, which means that the battery system it recommends is based on the household's own preference.
2. Our model can adapt to individual's energy consumption needs, as it takes into account the number of people, the size of the house, the average temperature and the energy habit.
3. Our model is comprehensive enough to give reliable suggestions on battery system selection. 8 factors – continuous power rating, usable capacity, cost, weight, volume, round-trip efficiency, lifespan and safety are considered.

4. Our model is convenient to use. Users only need to provide information on number of people, average temperature, size of the house and energy consumption habit, which are accessible in daily life.

6.4.2Weaknesses

1. The system contains only 8 batteries. There are many batteries available left unconsidered, and these may be able to form a system better than the current best choice. If there is more time given, we can take into account a greater range of batteries and the result would be more satisfactory.
2. The customers may not be able to give an accurate judgement of their energy consumption habit in percentage. Given more time, we can further develop a system asking several questions to determine the energy consumption habit in percentage.
3. The use time of electrical appliances may not correspond to real life situation. The house is imaginary and the use time is determined without the aid of actual usage data. If applicable, we can find a 1600-square-foot house and find the use time in real life context.

7 Alternative Energy Storage Plan (Problem 3)

7.1 Incorporating cement battery for our house

The cement batteries simulate the design of simple but long-lasting Edison batteries, in which an electrolyte solution carries ions between positively charged nickel plates and negatively charged iron ones, creating an electrical potential difference that produces voltage. In this case, conductive carbon fibers mix into cement (a main ingredient of concrete) substitute for the electrolyte. The researchers embed layers of a carbon-fiber mesh, coated in nickel or iron, to act as the plates.

7.2 Evaluation of cement battery

Advantages:

1. A house built by cement batteries would be beneficial in terms of sustainability. This design enables the current building materials to serve as another role, as such buildings can minimize waste by providing shelter and powering electronic appliances simultaneously.
2. Cement batteries are capable of discharging power and then recharging. The prototype is long-lasting — Edison batteries can operate for decades — and it resists overcharging. This battery can be exploited as much as one wants without imperiling the performance.

Disadvantages:

1. The contribution of cement batteries is not enough to compete with today's rechargeable devices when used for the whole household. Conventional batteries provide amps while cement batteries only provide milliamps. Conventional batteries work for days while cement batteries only work for hours. 200 square meters of the concrete can supply about 8 percent of the daily electricity consumption of a typical U.S. home. However, the cement-

based batteries are completely in their inception, their performance is expected to improve.

2. Changing cement batteries incorporated in the wall would be difficult and may ruin the structure of the houses. Concrete infrastructure usually can last fifty or even a hundred years, much longer when compared to cement batteries. Changing batteries in the wall would be very troublesome and cost a lot in terms of both time and money.

7.3 Comparing cement battery with other batteries

In order to compare cement batteries with existing batteries, basic information of the properties of cement batteries is needed. In this case, the 8 factors we previously considered for those 8 batteries should be put into account. However, the weight and volume can be excluded, because cement batteries are embedded in the walls and would not occupy extra space. Meanwhile, the size of the house, or the size of the walls, and the energy density is also needed, so that we can get the total amount of electricity which can be stored in the cement batteries through calculation. Hence, we need information on the continuous power rating, energy density, size of the wall, usable capacity, cost, weight, volume, round-trip efficiency, lifespan and safety of the cement batteries.

8 Reference

1. Saaty, Thomas L. "RANK GENERATION, PRESERVATION, AND REVERSAL IN THE ANALYTIC HIERARCHY DECISION PROCESS". Decision Sciences, vol 18, no. 2, 1987

2. Government of Santa Clara. “Appliance Energy Use Chart | Silicon Valley Power. ” Silicon Valley Power. https://www.siliconvalleypower.com/residents/save-energy/appliance-energy-use-chart.

3. Brady, Linda P. "Conflict Resolution: The Analytic Hierarchy Approach. Thomas L. Saaty , Joyce M. Alexander". The Journal Of Politics, vol 53, no. 1, 1991

4. Pudycheva, Halyna. "USING TOPSIS METHODS FOR SELECTION OF ELECTRICITY SUPPLIER". Pryazovskyi Economic Herald, 2021

5. "Roof With Solar Battery.". Vol 57, 1996

6. Yuniwati, Ika. "Correlation Test Application Of Supplier’s Ranking Using TOPSIS And AHP-TOPSIS Method". CAUCHY, vol 4, no. 2, 2016

7. Bushwick, Sophie. “Concrete Buildings Could Be Turned into Rechargeable Batteries - Scientific American.” Scientific American, Scientific American, 19 July 2021, https://www.scientificamerican.com/article/concrete-buildings-could-be-turned-into-rechargeable-batteries/.

8. Chalmers University of Technology. "Rechargeable cement-based batteries." ScienceDaily. ScienceDaily, 18 May 2021. <www.sciencedaily.com/releases/2021/05/210518114247.htm>.

9. Zhang, Emma Q., and Luping Tang. 2021. "Rechargeable Concrete Battery"

Buildings 11, no. 3: 103. https://doi.org/10.3390/buildings11030103
10. Li, Y., Pizer, W. A., & Wu, L. (2019, January 8). "Climate change and residential electricity consumption in the Yangtze River Delta, China." PNAS. Retrieved November 16, 2021, from https://www.pnas.org/content/116/2/472.

9 Appendix

9.1 Problem 1

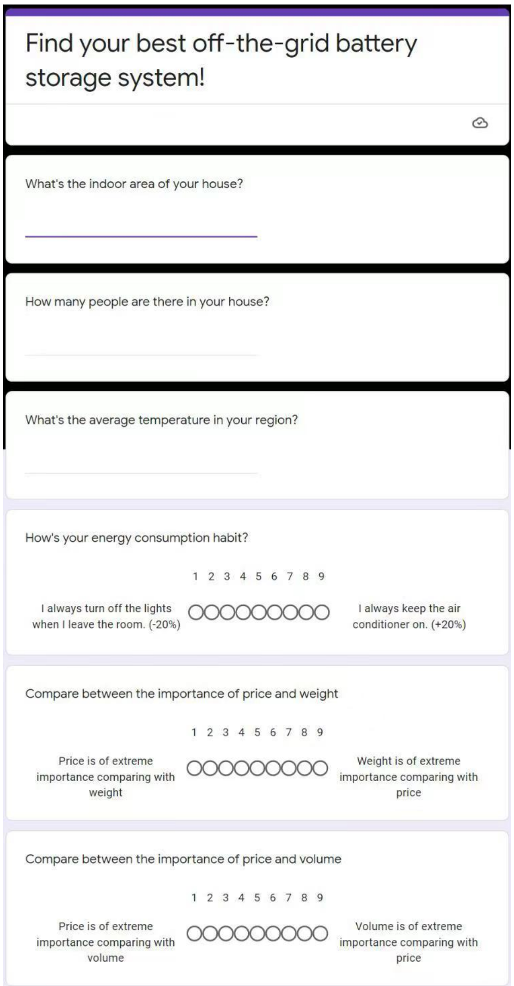
```
clc,clear,close all
ril=[0,0,0.58,0.90,1.12,1.24,1.32,1.41,1.43,1.49,
1.51];
a=[1 7 7 5 5 5;
1/7 1 1 1/3 1/5 1/5;
1/7 1/7 1 1/3 1/5 1/5;
1/5 3 3 1 2 1/2;
1/5 5 5 1/2 1 2;
1/5 5 5 2 1/2 1];
n1=size(a,1);
[x,y]=eig(a);
eigenvalue=diag(y);
lamda=eigenvalue(1);
cil=(lamda-n1)/(n1-1);
crl=cil/ril(n1);
wl=x(:,1)/sum(x(:,1));
%%
X=[5,8,9,7,9,9;
   3,7,7,8,9,9;
   8,8,8,4,1,1;
   1,1,1,1,9,9;
   7,6,1,7,9,9;
   4,9,8,9,3,1;
   6,9,8,7,1,1;
   9,7,7,7,9,9];
[n,m]=size(X);
Y=X;
wll=wl';
for i=1:n
  Y(i,:)=Y(i,:).*wll;
end
Z=Y;
%Z = Y ./ repmat(sum(Y.*Y) .^ 0.5, n, 1);
D_MAX = sum([(Z - repmat(max(Z),n,1)) .^
2 ],2) .^ 0.5;
D_MIN = sum([(Z - repmat(min(Z),n,1)) .^
2 ],2) .^ 0.5;
S = D_MIN ./ (D_MAX+D_MIN);
stand_S = S / sum(S);
%[sorted_S,index] = sort(stand_S ,'descend')
```

9.2 Problem 2

```
NP=input('Please input the number of people in
the household');
A=input('Please input the size of the house (in
square feet)');
TF=input('Please input the average temperature
of the area in winter(in degrees Fahrenheit)');
TC=(TF-32)*5/9;
Mu=input('Please describe energy consumption
habit by percentage between 80 and 120 (e.g.
100 means average level, 120 means much
above average)');
Mu=Mu/100;
D=input('Please input the maximum number of
consecutive days without sunshine');
P=Mu*1.075^(abs(TC-
11.4889))*(4875*A/1600+7750)/1000;
E=D*Mu*1.075^(abs(TC-
11.4889))*(log(NP+7.03331)-
1.20092)*(13.18*A/1600+16.6945);
Battery_CPR=[6.65,7.6,7,3.6,5,2.5,5,3.3];
No_CPR=ceil(P./Battery_CPR);
Battery_UC=[7.4,10,13.5,10,4.5,6.5,9.8,4];
No_UC=ceil(E./Battery_UC);
No=zeros(1,4);
Num=No';
for i=1:8
   No(1,i)=max(No_CPR(1,i),No_UC(1,i));
end
```

```
Battery_property=[6478   192   3616.935  0.95   30003
13000     346   12375      0.96  30003
8500 343.9        11750.508       0.90  100060
10990      447   27447.57813    0.85  30003
3999 176   15466       0.95  30003
5764 143   4814.4      0.98  150060
7500 220   8472.681  0.95  100060
2890 141   5739.52    0.95  30003];
for i=1:8
    for j=1:3
        Battery_property(i,j)=Battery_property(i,j)*No(i);
    end
end
[n,m]=size(Battery_property);
Y=Battery_property;
for i=1:3
   Y(:,i)=1./Y(:,i);
end
Y(:,6)=1./Y(:,6);
Y = Y ./ repmat(sum(Y.*Y) .^ 0.5, n, 1);
disp('Please complete ajudgement matrix comparing a pair of factors to get the relative weight ranging from 1 to 9');
disp('Factors:');
disp('1.Cost; 2.Weight; 3.Volume; 4.Round-trip efficiency; 5.Battery life; 6.Safety');
F_jm=input('Please input a 6×6 matrix');
n1=size(F_jm,1);
[xx,yy]=eig(F_jm);
eigenvalue=diag(yy);
lamda=eigenvalue(1);
cil=(lamda-n1)/(n1-1);
crl=cil/1.24;
while crl>0.1
    disp('Matrix INVALID');
    F_jm=input('Please input a 6×6 matrix');
end
while crl<0
    disp('Matrix INVALID');
    F_jm=input('Please input a 6×6 matrix');
end
wll=xx(:,1)/sum(xx(:,1));
w=wll';
for i=1:n
    Y(i,:)=Y(i,:).*w;
end
z=Y;
D_MAX = sum([(z - repmat(max(z),n,1)) .^ 2 ],2) .^ 0.5;
D_MIN = sum([(z - repmat(min(z),n,1)) .^ 2 ],2) .^ 0.5;
S = D_MIN ./ (D_MAX+D_MIN);
stand_S = S / sum(S);
```

9.3 Our program



Monday, Nov 15, 2021

THE DAILY NEWS

CHOOSING THE BEST BATTERY FOR HOMES WITH EASE

By Team #11558

For those who live in remote areas and use solar panel together with off-grid energy storage systems to power their house, choosing suitable batteries is always a big trouble. Fortunately, a team has recently developed a model to help people make their choices. By using this model, you can easily know the best type of battery that satisfy both your energy needs and personal preferences.

Firstly, it requires you to provide your home's basic information such as number of occupants, size of their house and weather. Then it will estimate the energy requirements of your house by multiple functions. In this way the model creates a list of battery plans that satisfy your energy needs.

To evaluate the best option for each home, it needs you to rank the importance of 6 factors of batteries which are costs, weights, volume, efficiency, lifespan and safety.

According to the importance and the score of each factor for each battery, the model will rank those battery plans and finally give the best recommendation.

With this recent developed model, there's no need for people to scanning dazzling advertisements or searching for information about parameters that they cannot understand. If you are one of those people desperately looking for best batteries for their homes, you would probably want to try this model.

WILL OUR BUILDINGS BECOME BATTERIES?

Sustainability has become a core issue in today's context of global warming. For the sake of sustainability in architectural industry, cement batteries have become a new alternative that may help reduce carbon footprint in building significantly.

Cement batteries are made by adding conductive carbon fiber in the concrete and embedding electrodes inside. Buildings' walls and roofs made by cement batteries can store large amounts of solar power. This makes buildings self-sufficient and sustainable, because now they can house people and power electricity appliances simultaneously.

Also, cement batteries do not occupy extra space, as they are put inside the walls and roofs. Furthermore, cement batteries do not use toxic or expensive materials.

However, this technology is relatively new when compared to other batteries available in the market. The capacity is quite low and is not sufficient to power the whole household. We believe that as this technology develops, this problem would be improved greatly.