Analytic Hierarchy Process Selection for Batteries Storage Technologies

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Abstract: The objective of this study is to select the most appropriate battery technology for photovoltaic application. However, the selection criteria and the diversity of technologies make choice difficult. So, we focus on the Analytic Hierarchy Process which is among the most widely used and has been applied in several multicriteria decision making domains.

Keywords: Battery technology; selection; multi criteria; AHP

I. INTRODUCTION

Today, there is a continuous need for more energy [1], the source must provide immediate response to these increasing demands of power. Thus, the energy storage and the electrochemical storage systems which are batteries are becoming increasingly important.

Batteries are applied in several domains [3] of applications such as photovoltaic, telecommunication, spatial, vehicle, agricultural,…

Seven technologies of batteries [4], which are: Lead-Acid batteries [6], Nickel-Cadmium [5], Nickel-Metal Hydride [5, 7,8], Nickel-Zinc [5], Nickel-Hydrogen [5,9], Lithium-Ion [10] and Supercapacitor [11], will be compared using the Analytic Hierarchy Process (AHP) according to six criteria which are sizing, efficiency, lifetime, self discharge rate, environment and cost.

The selection criteria will serve to make comparisons [2] in order to determine the most appropriate technology for each type of application.

II. BATTERIES TECHNOLOGIES

Our purpose is to compare seven batteries technologies: Lead-Acid batteries [6], Nickel-Cadmium [5], Nickel-Metal Hydride [5, 7,8], Nickel-Zinc [5], Nickel-Hydrogen [5,9], Lithium-Ion [10] and Supercapacitor [11]. The comparison is made taking into account six criteria which are sizing, efficiency, lifetime, self discharge rate, environment and cost.

1. Sizing criterion (C1)
The sizing criterion describes the amount of energy or power to be stored per unit of mass or volume of the storage element. To evaluate this criterion, we will consider three sub- criteria which are mass energy density (C11), volume energy density (C12) and power density (C13).

2. Lifetime criterion (C2)
The lifetime criterion is expressed as the number of cycles (one cycle corresponds to one charge and discharge). This parameter refers to the time of storage on which the system can release the energy level. It depends on the type of storage and the type of application.

3. Efficiency criterion (C3)
The storage system must have a good efficiency to be competitive. However, the energy storage technology must have limited losses in terms of energy and self-discharge.

4. Self-discharge rate (C4)
The self discharge rate represents the time for which the stored energy has dissipated over an amount of non use time.

5. Environment (C5)
Environment criterion is an important parameter for an energy storage technology that will be vital to a future clean energy landscape.

6. Cost per kWh (C6)
Energy storage system is an interesting investment. High efficiency and high lifetime require highest investment for a given application. The cost of batteries includes the cost of the metal that constitutes the electrode of each electrochemical element. Further to the London Metal Exchange [12], the metal prices have had rocky times but they show some signs of recovery. This is illustrated by figure 1, 2 and 3.

Figure 1. Lead prices $ US per ton [12]
In order to select the most appropriate battery technology according to the evaluation table (table 1), the choice is almost difficult. In the following, the principle of the AHP method is developed.

### III. THE AHP METHOD

The concept of AHP was developed by Thomas Saaty. AHP is an approach to decision making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives [13]. By organizing and assessing alternatives against a hierarchy of multifaceted objectives, AHP allows a better, easier, and more efficient identification of selection criteria, their weighting and analysis [14]. Thus, AHP reduces drastically the decision cycle. AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluation measures and alternatives, thus reducing bias in decision making [13,14].

### I. Step 1 : Hierarchy structure

The first step of AHP is to develop a decision hierarchy with an objective, alternatives and criteria. As shown by figure 4, four-levels are considered.

The objective, placed in level 1, is to select the most appropriate technology of batteries from eight alternatives (options). There are six criteria, placed in level 2, that enter into this decision: sizing (C1), lifetime (C2), efficiency (C3), self discharge rate (C4), environment (C5) and cost (C6). The sizing criterion has three sub-criteria, placed in level 3,: mass energy density (C11), volume energy density (C12) and power density (C13).

The alternatives are placed in the last level: lead battery(A1), Nickel-Cadmium (Ni-Cd)(A2), Nickel-Metal-Hydride (Ni-MH) (A3), Nickel-Zinc (Ni-Zn) (A4), Nickel-Hydrogen (Ni-H$_2$) (A5), Lithium-Ion (Li-Ion) (A6) and Super-capacity (A7).
2. **Step 2: Pairwise Comparisons**

The second step is to calculate the relative importance of each criterion and each alternative according to each criterion by means of pairwise comparisons and a 9-point system ranging from 1 to 9. As shown in table 2, these values are in practice assigned by verbal elicitation of decision makers. However, if one criterion (or alternative) is preferred less than the compared criterion (or alternative), the reciprocal of the preference score is assigned (1/9th to the 9-point scale has been the standard rating system used for the AHP [13]).

![Diagram](image)

**Figure 4. The hierarchical setup**

### Table 2. The Fundamental AHP Scale

<table>
<thead>
<tr>
<th>Numerical Rating</th>
<th>Verbal judgment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Extreme importance</td>
</tr>
<tr>
<td></td>
<td>Intermediate values for the scale</td>
</tr>
</tbody>
</table>

Tables 3 and 4 describes the highest-level attribute classifications criteria, sizing (C1), lifetime (C2), efficiency (C3), self discharge rate (C4), environment (C5) and cost (C6). This table is obtained after rigorous investigations in the photovoltaic application.

![Table 3](image)

**Table 3. A Pair-wise Comparison Matrix for the Criteria Level**

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1</td>
<td>1/7</td>
<td>1/3</td>
<td>1/5</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>7</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>3</td>
<td>1/3</td>
<td>1</td>
<td>½</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>C4</td>
<td>5</td>
<td>1/2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>C5</td>
<td>2</td>
<td>1/5</td>
<td>1/2</td>
<td>1/3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>1/2</td>
<td>1/9</td>
<td>1/5</td>
<td>1/7</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

![Table 4](image)

**Table 4. A Pair-wise Comparison Matrix for the Sub-Criteria**

<table>
<thead>
<tr>
<th></th>
<th>C11</th>
<th>C12</th>
<th>C13</th>
</tr>
</thead>
<tbody>
<tr>
<td>C11</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>C12</td>
<td>1/5</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td>C13</td>
<td>1/3</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Each element $a_{ij}$ of the comparison matrix is a numerical value, representing the importance of the $i^{th}$ factor over the $j^{th}$ factor. Consequently, it represents a ratio between weight concerning the element $i$ (Pi) and weight concerning the element $j$ (Pj). A normalized pairwise comparison matrix $[A]$ is given by (1).

$$A = \frac{\begin{bmatrix} P_1 & P_2 & \cdots & P_n \\ P_1 & P_2 & \cdots & P_n \\ \vdots & \vdots & \ddots & \vdots \\ P_1 & P_2 & \cdots & P_n \end{bmatrix}}{1}$$

(1)
3. Step 3: priority vector calculation

A priority criteria weight vector \( W \) is determined by dividing each element of the matrix \( A \) by its column total to obtain in Table 5 the normalized pairwise rating of selection criteria. The judgment matrix \([A]\) is changed into a new Matrix \([A']\) (2).

\[
[A] = \left[ \frac{1}{\sum a_{ii}} a_{i1}, \frac{1}{\sum a_{2i}} a_{i2}, \ldots, \frac{1}{\sum a_{ni}} a_{in} \right]
\]

(2)

Add all the elements of each row in matrix \([A']\), gives a principal eigenvector \( W \) of the judgment matrix \([A]\), consequently the local priority vector can be generated by the normalized eigenvector \( W \). The priority vector ranks the variables in order of importance depending on the pair wise comparisons.

\[
W = [W_1, W_2, W_3, \ldots, W_n]^T
\]

(3)

Where \( CI \) is the consistency index described in (8) and \( RI \) is the Random Index provided by Saaty [..] (table 6). The consistency index \( CI \) is defined as:

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]

(8)

Once the scoring and synthesis process has been completed for the criteria, it is conducted for the sub-criteria and alternatives. The pair-wise comparison matrix of sub-criteria is given in table 7. The pair wise comparison of alternatives according to each sub-criterion/criterion and their respective weights are depicted in tables 8, 9, 10,11,12,13, 14 and 15.

The pair wise comparison of the different alternatives according to C1 is made by the pair wise comparison of the alternatives according to the different sub-criteria.

\[
W_i = \frac{1}{n} \sum_{j=1}^{n} p_{ij}
\]

(4)

\[
p_i = \left[ \frac{1}{\sum a_{ij}} a_{i1}, \frac{1}{\sum a_{ij}} a_{i2}, \ldots, \frac{1}{\sum a_{ij}} a_{in} \right]
\]

(5)

The maximal eigen value of the judgment matrix \([A]\) is given by the following:

\[
\lambda_{\text{max}} = \sum [(A]W_i, /W_i]
\]

(6)

To measure the consistency of the comparison matrix, a consistency ratio CR defined as:

\[
CR = \frac{CI}{RI}
\]

(7)

CR of 0.1 or less is considered acceptable.
Once the different priority vectors are calculated, the next step is to determine the global importance vector of alternatives.


The global priority is obtained by multiplying the 1 x 5 “criteria vector” W by the 5 x 7 “alternatives matrix”. Table 15 illustrates the results of global ranking. Results show the Li-Ion (A6) battery technology is best alternative and the A7 super-capacitor is placed second.

Table 15. Normalized weighted preference scores

<table>
<thead>
<tr>
<th>Battery technology</th>
<th>Global weight</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-Acid</td>
<td>0.130</td>
<td>4</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>0.120</td>
<td>5</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>0.059</td>
<td>7</td>
</tr>
<tr>
<td>Ni-Zn</td>
<td>0.065</td>
<td>6</td>
</tr>
<tr>
<td>Ni-H2</td>
<td>0.135</td>
<td>3</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>0.247</td>
<td>1</td>
</tr>
<tr>
<td>Super-Capacity</td>
<td>0.241</td>
<td>2</td>
</tr>
</tbody>
</table>
In this paper, the AHP method is applied to choose the most advantageous battery technology between seven different technologies and according to six criteria. The pair-wise rating of each battery technology with respect to each criterion is approved by evaluating the different values for each alternative in each criterion. The evaluation of the different criteria for each alternative showed that there is no alternative having the best performance then the others according to all criteria. The AHP method gives the best compromise between the different studied batteries technologies.

REFERENCES


[12] London Metal Exchange http://www.lme.co.uk


