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An Analytic Hierarchy Process for Selecting Battery Equalization Methods

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Abstract: Batteries have been the predominant energy storage system used in electric vehicles. Battery packs have a large number of cells that develop charge, thermal, and capacity imbalances over time, limiting the power, range, and lifetime. Electronic battery management and state of charge (SoC) equalization methods are necessary to mitigate such imbalances. Today, it is possible to find a wide range of battery equalization methods in the literature, but how to decide which of these methods should be applied in practice? This paper compares 24 SoC equalization circuits that are typically found in automotive applications. We employ an analytic hierarchy process (AHP) approach to rank these equalization circuits according to multiple decision criteria (energy efficiency, equalization speed, implementation and control simplicity, hardware size, and total price). We also prepared a survey to collect design preferences from multiple battery balancing experts from around the world in order to better understand the relative importance of different criteria. The obtained results confirm that automotive engineers continue to favor passive balancing methods because of their low price, small PCB size, and implementation simplicity—despite the energy efficiency benefits of active balancing.

Keywords: battery; energy management system; EMS; battery management system; BMS; state of charge equalization; balancing system; costs analysis for practical application; analytic hierarchy process; AHP; electric vehicle; plug-in hybrid electric vehicle

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1. Introduction

Most transportation systems in land, air, and sea, depend on fossil fuels [1]. Due to global climate change, reducing greenhouse gas emissions is of the utmost importance. To achieve this, the automotive industry has been making strong commitments toward battery-based electric vehicles [2] as a way to reduce air pollutant emissions [3,4]. However, to be competitive, batteries must be affordable and they must offer a long lifetime and the same or a higher range to vehicles when compared to traditional internal combustion engine vehicles [5,6].

1.1. Main Issues and Characteristics of Battery Cells

One of the main issues in the design of battery-based electric vehicles is non-uniformity in the capacity, inner impedance, and thermal characteristics of the battery cells. This may result in performance degradation, limited by the cell with the poorest performance, i.e., the 'weakest-cell problem' [7]. Cells with the least chargeable or dischargeable capacities limit the capacity and longevity of the battery pack [8,9]. The causes of battery pack inconsistency are diverse. They are often dependent on materials, assembly techniques, fabrication factors, etc. [9]. These inconsistencies can be caused by internal and/or external causes. Internal factors include internal resistance, cell capacity, and the self-discharge rate; external factors include ambient temperature, depth of discharge, and the charging and the discharging current. During the normal operation of a battery pack, the coupled effect of internal and external factors leads to inter-cell inconsistency. For example, overcharging can give rise to unwanted internal chemical reactions, which increase internal cell pressure and temperature. This can accelerate battery aging and damage and even trigger fires and/or explosions in extreme cases [7,8].

It should be noted that battery cells are electrochemical systems with uncertainties at the material level due to unavoidable variability in the manufacturing and the operating conditions of the battery. Each cell has a unique self-discharge rate, nominal capacity, impedance, open circuit voltage (OCV), and state of charge profile, which can vary over time [10–14]. These cell-to-cell differences pose several operational challenges. For example, cells with lower capacities are at a higher risk of being exposed to overvoltage during charging, which may lead to capacity fade and a shorter lifespan. During discharging, these cells also limit the maximum power that can be extracted from the battery pack, constraining the vehicle's range per charge. Furthermore, there is a positive feedback mechanism, where cell-to-cell variations induce an unbalanced SoC and an unbalanced SoC increases cell-to-cell variations [15].

To address these cell-to-cell imbalances, numerous cell equalization methods have been proposed, ranging from bypass to passive and active methods [1]. Each method has different strengths and weaknesses. For example, the bypass and passive methods are simple to implement and they have reduced costs but they suffer from low energy efficiency. Active balancing approaches have complementary strengths but they are generally more complex and more expensive due to the use of additional electronics [16–19].

1.2. Objectives and Contributions

The objective of this paper is to develop practical tools that can help select SoC equalization methods for large battery packs. To accomplish this, 24 equalization methods are evaluated and ranked based on a worldwide survey that collected experts' opinions on their design preferences. First, the experts were asked to choose the five most important design criteria to design final electronic projects from among the options presented. The collected data was then processed with an analytic hierarchy process (AHP) methodology, enabling us to rank the equalization methods according to different criteria, such as (i) energy efficiency, (ii) equalization speed, (iii) implementation and control simplicity, (iv) hardware size, and (v) total price, which were the criteria chosen by the experts in the survey.

1.3. Related Work

Selecting a SoC equalization circuit for battery packs is not an easy task due to the wide range of options and the evaluation criteria [8,19,20]. One approach for this selection problem relies on numerical simulation [21]; this allows rigorous quantification of performance metrics for different balancing circuits but at the expense of high development efforts, especially to build mathematical models for the converters. Another approach consists of ranking the SoC equalization electronics based on the designer's individual perception of the strengths/weaknesses of each circuit [22,23]; although it offers quick decisions, this brings individual bias to the selection problem.

This work offers an alternative approach. It proposes an AHP to fuse the opinion of multiple experts in the evaluation of the SoC equalization circuit as a means to reduce individual bias. The AHP methodology is usually employed in complex, multicriteria decisions where evaluation metrics are difficult to numerically quantify; AHP divides the decision problem into smaller subject-matter areas that are then ranked by different groups of experts. Individual bias is reduced by fusing the preferences of multiple experts.

This methodology has been applied widely in a broad range of areas, such as investment analysis, sustainable development, and engineering projects [24]. Recently, AHP has been employed to evaluate energy storage systems. For example, in [25], AHP was used to select battery chemistries in grid applications, while [26] used AHP to evaluate the safety of automotive lithium-ion batteries. In [27], AHP was exploited to select charging stations for hydrogen/battery buses; and, in [28], AHP was used to develop a dual estimation framework to evaluate the maximum available energy of lithium-ion batteries. To the best of the authors' knowledge, AHP has not been applied to select battery SoC equalization methods in automotive applications.

2. Cell Equalization Methods

There are two main classes for cell equalization: passive and active. In passive equalization, resistors are connected in parallel to cells to dissipate the energy of the cells with the highest voltage/charge. In active equalization, the equalization process is performed by transferring the excess charge from overcharged cells to another cell, module, or pack using electronic circuits [1,4,7,8,29]. These circuits use capacitors, transistors, transformers, converters, and inductors to transfer energy among the cells. Figure 1 presents the most used equalization methods and the AHP hierarchy model developed for the decision-making process according to the objectives in Section 1.2. They are mainly categorized in the following class schemes:

- Passive methods: [1.1] Cell Bypass (CB), [1.2] Cell-to-heat (CH);
- Active methods: [2.1] Cell-to-Cell Shared (CCS) or Distributed (CCD), [2.2] Cell-to-Pack (CP), [2.3] Pack-to-Cell (PC), and [2.4] Cell-to-Pack-to-Cell (CPC).

For practical application, passive equalization is the most often used due to its low cost, low computation, and implementation complexity [1]. Yet, it is the most energy inefficient, resulting in heat generation and excessive energy losses.

Active equalization offers better energy efficiency. In Cell-to-Cell Shared, the energy is transferred from a cell to an accumulator element and from that element to the desired cell or cells [20]. In Cell-to-Cell Distributed, the equalization is made from adjacent cells. The costs of these method are generally higher than passive methods due to the large number of electronic components [1]. Cell-to-Pack transfers the energy from the desired cell to the whole battery pack, while in the Pack-to-Cell method, the energy is transferred from the battery pack to a desired cell [30]. Lastly, the Cell-to-Pack-to-Cell method can transfer energy from a cell or a set of cells to the whole pack and vice-versa. Compared to all energy transfer types, CPC requires a reduced number of electronic components, but the costs are higher due to the large voltage boost that is necessary from the cell to the pack [30].

A brief review of these equalization methods is presented in the Supplementary Files, which are available in [31]. The reader is also referred to [8,19,20], where comprehensive reviews and detailed analyses of existing methods are presented.

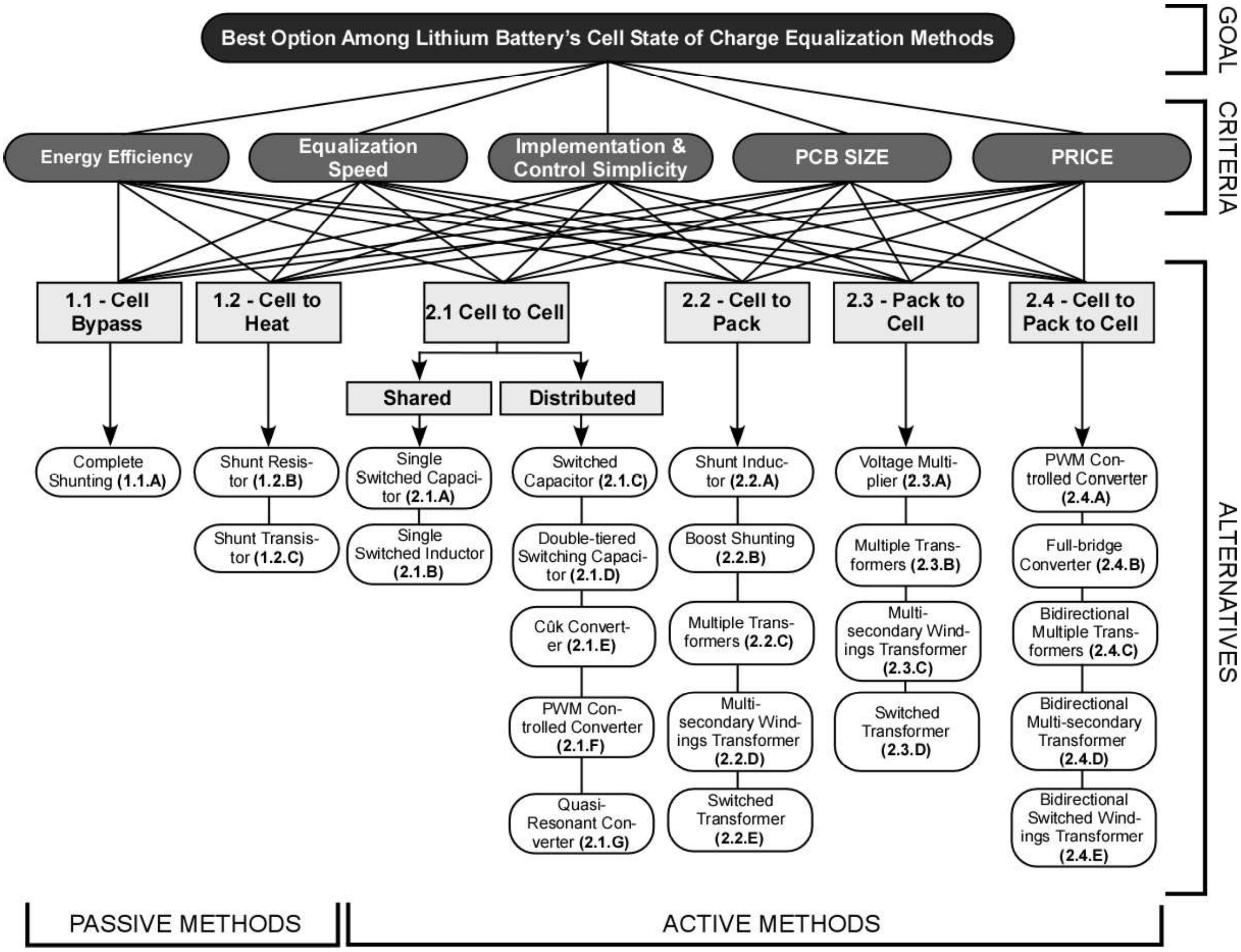


Figure 1. State of Charge Equalization Methods classified according to the energy transfer configuration. 1.1 Cell Bypass (CB), 1.2 Cell-to-Heat (CH), 2.1 Cell-to-Cell Shared (CCS), 2.1 Cell-to-Cell Distributed (CCD), 2.2 Cell-to-Pack (CP), 2.3 Pack-to-Cell (PC) and 2.4 Cell-to-Pack-to-Cell (CPC).

3. Method: Analytic Hierarchy Process

Different SoC equalization circuits have different pros and cons in terms of energy efficiency, cost, and size, among other aspects. At first glance, it is not immediately clear which method provides the best tradeoff among all design criteria. To address this issue, we prepared a survey to collect the opinion of multiple experts from all over the world. The experts were asked to rank equalization circuits according to different evaluation criteria (energy efficiency, equalization speed, cost, size, and implementation simplicity). The results of the survey are presented in Section 4, and they were used as input to the AHP to determine the best equalization circuits.

A multicriteria decision-making technique, AHP makes use of pairwise comparisons to fuse and to weight the experts' opinions. It was originally developed by L. Saaty in the 1970s [32]. It is a general problem-solving method that is useful in making complex, multicriteria decisions based on variables that do not have exact numerical consequences. The AHP relies on a theory of relative measure based on the pairwise comparison. It uses normalized tables of absolute numbers whose elements are then used as priorities. As it is a multicriteria process, it should match the priorities of the alternatives derived under different criteria [33–36].

The pairwise comparisons indicate how much more important one design factor is in relation to another. The AHP numerical scale varies from 1 to 9, where 1 implies equal importance between two design criteria, and 9 indicates that one criterion is much more important than the other [32]. Table 1 presents the scales used in AHP comparison analysis.

Table 1. Scales used in AHP comparison analysis.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another
7	Demonstrated importance	A criterion is strongly favored, and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If criteria i has one of the above nonzero numbers assigned to it when compared with criteria j, then j has the reciprocal value when compared with i	
Rational	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

Source: Adapted from [32].

The AHP relies on the following steps [35,37]:

1. Define the problem and the decision that needs to be made. In the presented work, the problem consists in selecting a battery SoC equalization circuit for a given application. Next a hierarchy model is established based on an analysis of the problem. A decision hierarchy is built from the top with (i) the decision goal, (ii) the criteria $(C_1, C_2, \ldots, C_n)$ that will be used to evaluate the fulfillment of the goal, and (iii) a set of design alternatives (see Figure 1). In this work, there are five design criteria [energy efficiency (C_1), equalization speed (C_2), implementation simplicity (C_3), hardware size (C_4), and price (C_5)]; and there are 24 alternatives or methods for the SoC equalization circuit as presented in Figure 1;
2. Pairwise comparison matrices $A \in R^{n\times n}$ are formed among the design criteria. Each element $A(i,j)$ in the pairwise comparison matrix (A) depicts an individual judgment of the relative importance between the pair of (i_{th}) and the (j_{th}) design criteria using the ratio scale method shown in Table 1. In the presented work, a worldwide survey collected experts' opinions to define this judgment. The importance between the same opposite pair, e.g., the (j_{th}) and the (i_{th}) factors, must be the inverse of the (i_{th}) and the (j_{th}) ratio scale as shown in Table 2. For example, following the scales shown in Table 1, the expert can strongly favor the price $(i = 5)$ over the speed $(j = 2)$ in their pairwise comparison judgment, yielding $A_{(5,2)} = 9$; and $A_{(2,5)} = 1/9$;
3. To give the relative weights of criteria, each eigenvalue (λ_i) of the eigenvector (λ) must be calculated using the geometric mean at the criterion data set of the pairwise comparison matrix (A) formed at the previous step. Thefore, the individual components of λ, denoted λ_i, are defined as:

$$\lambda_i = \prod_{i=1}^{n} A_{ij}^{1/n} \tag{1}$$

4. Calculate the criteria vector $[\boldsymbol{C_j}]$ by summing the rows of $\boldsymbol{A}$:

$$[\boldsymbol{C_j}] = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{A_{ij}} \tag{2}$$

For $j = 1, \ldots n$;

5. Determine the weight vector (W). The priorities obtained from the pairwise comparison matrix (A) are used to define the importance of each criterion toward the decision goal. The components of the weight vector (W_i) are proportional to λ_i:

$$W_i = \frac{\lambda_i}{\sum \lambda_i} \tag{3}$$

For $i = 1, \ldots n$.
Note that the denominator is the previous expression that normalizes W_i:

$$\sum W_i = 1 \tag{4}$$

6. Calculate the maximum eigenvalue (λ_{max}) using (W_i) and the criteria vector $[C_j]$:

$$\lambda_{max} = [W_i] \times [C_j] \tag{5}$$

7. Compilation of the alternative matrix $\alpha^{(k)} \in R^{n \times n}$. Given a specific SoC equalization circuit ($k \in [1, 24]$), each criterion ($c_1,\ c_2,\ \ldots, c_n$) must be evaluated on a scale of 1 to 9. For this research work, the scale was defined as bigger is better for energy efficiency (C_1) and equalization speed (C_2); and, it was defined as smaller is better for implementation effort (simplicity) (C_3), hardware size (C_4), and price (C_5);
8. Normalization of the alternative matrix ($\alpha^{(k)}$) to obtain a global scale in a range of 0 to 1 for every alternative of the matrix ($\alpha_{ij}^{(k)}$). The normalization techniques must be done before the values being used to calculate the AHP decision profile matrix (δ), and they must consist of dividing every entry in a vector by its magnitude to create a vector of length one known as the unit vector [32]. The normalized value for each entry $\alpha_{ij}^{(k)}$ is calculated as:

$$Norm_{\alpha_{i,j}}^{(k)} = \frac{\alpha_{ij}^{(k)}}{\sum_{j=1}^{k} \alpha_{ij}^{(k)}} \tag{6}$$

9. Still, from a descriptive point of view, it will be important to develop a common understanding among the criteria; and, for this purpose, sometimes an additional harmonization process is required before calculating the normalized alternative matrix ($Norm_{\alpha_{i,j}}^{(k)}$). This step should be executed only if the specific criterion (C_n) was defined to be better as smaller per the value on the AHP scale is (see step 7). Harmonization involves improving comparability of similar measures collected by separate databases and different individuals. Thus, these criteria were first harmonized accordingly to Equation (7) and then the normalization process occurred according to Equation (8);

$$Harm_{\alpha_{i,j}}^{(k)} = \frac{\alpha_{ij}^{(k)}}{\sum_{j=1}^{k} \alpha_{ij}^{(k)}} \tag{7}$$

$$Norm_{\alpha_{i,j}}^{(k)} = \frac{Harm_{\alpha_{i,j}}^{(k)}}{\sum_{j=1}^{k} Harm_{\alpha_{i,j}}^{(k)}} \tag{8}$$

10. The consistency of judgments is checked. The AHP also calculates an inconsistency index to reflect the consistency of decision makers' judgements during the evaluation

phase. The consistency index (CI) and the consistency ratio (CR) are measured for each pairwise comparison matrix. CI is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (9)$$

where (λ_{max}) and n are the maximum eigenvalue and the quantity of design criteria, respectively. The judgment is consistent only if $(CI \leq 0.1)$; otherwise, the judgment should be revised. The CR is defined as:

$$CR = \frac{CI}{RI}, \quad (10)$$

where (RI) is a set of given average random consistency indices—given by [38] and illustrated at Table 3, which is an index whose value varies according to the quantity of design criteria defined for AHP, and it can be obtained using statistical calculations [36]. If (CR) is no larger than 10%, the inconsistency of judgments is acceptable. Otherwise, the judgments need to be revised [39];

11. Finally, as Equation (11) demonstrates, the AHP decision profile matrix (δ) can be calculated as the sum of products between the normalized alternative matrix $(Norm^{(k)}_{\alpha_{i,j}})$ and the weight vector (W) calculated at step 5.

$$\delta = \sum \left[Norm^{(k)}_{\alpha_{i,j}} \right] \times [W_{i,j}] \quad (11)$$

Table 2. Calculations to obtain pairwise comparison matrix A.

Criteria	Energy Efficiency	Equalization Speed	Implementation Simplicity	Hardware Size	Total Price	Eigenvector (λ)	Weight Vector (W)
	C_1	C_2	C_3	C_4	C_5	(λ_i)	(w_i)
C_1	$[A_{11}] = 1$	$[A_{12}]$	$[A_{13}]$	$[A_{14}]$	$[A_{15}]$	$\lambda_1 = \prod_{i=1}^{n=5} A_{ij}^{\frac{1}{n}}$	$W_1 = \frac{\lambda_1}{\sum \lambda_i}$
C_2	$[A_{21}] = \frac{1}{[A_{12}]}$	$[A_{22}] = 1$	$[A_{23}]$	$[A_{24}]$	$[A_{25}]$	$\lambda_2 = \prod_{i=2}^{n=5} A_{ij}^{\frac{1}{n}}$	$W_2 = \frac{\lambda_2}{\sum \lambda_i}$
C_3	$[A_{31}] = \frac{1}{[A_{13}]}$	$[A_{32}] = \frac{1}{[A_{23}]}$	$[A_{33}] = 1$	$[A_{34}]$	$[A_{35}]$	$\lambda_3 = \prod_{i=3}^{n=5} A_{ij}^{\frac{1}{n}}$	$W_3 = \frac{\lambda_3}{\sum \lambda_i}$
C_4	$[A_{41}] = \frac{1}{[A_{14}]}$	$[A_{42}] = \frac{1}{[A_{24}]}$	$[A_{43}] = \frac{1}{[A_{34}]}$	$[A_{44}] = 1$	$[A_{45}]$	$\lambda_4 = \prod_{i=4}^{n=5} A_{ij}^{\frac{1}{n}}$	$W_4 = \frac{\lambda_4}{\sum \lambda_i}$
C_5	$[A_{51}] = \frac{1}{[A_{15}]}$	$[A_{52}] = \frac{1}{[A_{25}]}$	$[A_{53}] = \frac{1}{[A_{35}]}$	$[A_{54}] = \frac{1}{[A_{45}]}$	$[A_{55}] = 1$	$\lambda_5 = \prod_{i=5}^{n=5} A_{ij}^{\frac{1}{n}}$	$W_5 = \frac{\lambda_5}{\sum \lambda_i}$
C_j	$= \sum_{i=1}^{n}(A_{i1})$	$= \sum_{i=1}^{n}(A_{i2})$	$= \sum_{i=1}^{n}(A_{i3})$	$= \sum_{i=1}^{n}(A_{i4})$	$= \sum_{i=1}^{n}(A_{i5})$	$\sum \lambda_i$	$\sum W_i = 1$
	Eigenvalue $\boldsymbol{\lambda_{max}}$				$[W_i] \times \left[C_j\right]$		
CI	$\frac{\lambda_{max} - n}{n-1}$		$\boldsymbol{n}$ = total criteria	**R1** = Table 3	**CR**	$\frac{CI}{RI}$	

Source: Adapted from [35].

For the realization and the analysis of judgments, the AHP works with a decision square matrix of order n and the eigenvectors related to them. Table 2 summarizes the eleven steps above, and it shows an example of the AHP, with the most important variables.

Table 3. The Random Index (RI).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.52	0.89	1.11	1.25	1.5	1.40	1.45	1.49

Source: Adapted from [39].

Ease of application is one of the main advantages of the AHP method, since only two alternatives at a time need to be evaluated. This feature is particularly helpful in case of a large number of design alternatives [40]. Another advantage comes with an ability to assess the consistency of the pairwise comparisons. In an ideal case, the largest eigenvalue is equal to the number of alternatives. When some level of inconsistency appears, the eigenvalue becomes higher [32]. Additionally, the results of the AHP can be conveniently captured and visualized in the form of a so-called decision profile (Equation (11)). It offers a convincing view of the results of rating the alternatives and the associated quality of the process.

4. Results and Discussion

In this section the AHP method is applied to select the best SoC equalization method. The main assumptions that we considered were:

1. We considered a road vehicle with 100 lithium iron phosphate cells in series with a total nominal voltage of 320 V, a common battery pack configuration used in today's electric vehicles;
2. Every SoC equalization method should be able to transfer or dissipate up to 10 Ah of electric charge between the cells or the battery pack;
3. The price and the PCB Size criteria will be calculated equally between all methods according to assumptions 1 and 2 above.

4.1. Survey

To generate data for the AHP, experts from all over the world were invited to answer a survey regarding design preferences for battery SoC equalization. A web-based form was developed and published online from 1 September to 1 October 2021. The survey was sent to 1988 experts who published technical papers on battery equalization electronics over the last decade. The survey was accessed by 426 participants; from these, 42 finished the survey (10% finish rate), representing a wide range of countries from Europe, America, Asia, and Oceania.

The survey was divided into two parts. In the first part (presented in Figure 2), the goal was to capture the value for pairwise comparisons between different design criteria, i.e., to indicate the importance of one design criterion versus another (see Table 1). This allowed the generation of data to apply step 2 of Section 3 and build the comparison matrix A. More specifically, each expert was asked to perform the following pairwise comparisons:

- (c_3) Implementation and Control Simplicity VS. (c_4) Hardware and PCB Size;
- (c_3) Implementation and Control Simplicity VS. (c_5) Total Price;
- (c_1) Energy Efficiency VS. (c_3) Implementation and Control Simplicity;
- (c_1) Energy Efficiency VS. (c_4) Hardware and PCB Size;
- (c_1) Energy Efficiency VS. (c_5) Total Price;
- (c_1) Energy Efficiency VS. (c_2) Equalization Speed;
- (c_4) Hardware and PCB Size VS. (c_5) Total Price;
- (c_2) Equalization Speed VS. (c_3) Implementation and Control Simplicity;
- (c_2) Equalization Speed VS. (c_4) Hardware and PCB Size;
- (c_2) Equalization Speed VS. (c_5) Total Price.

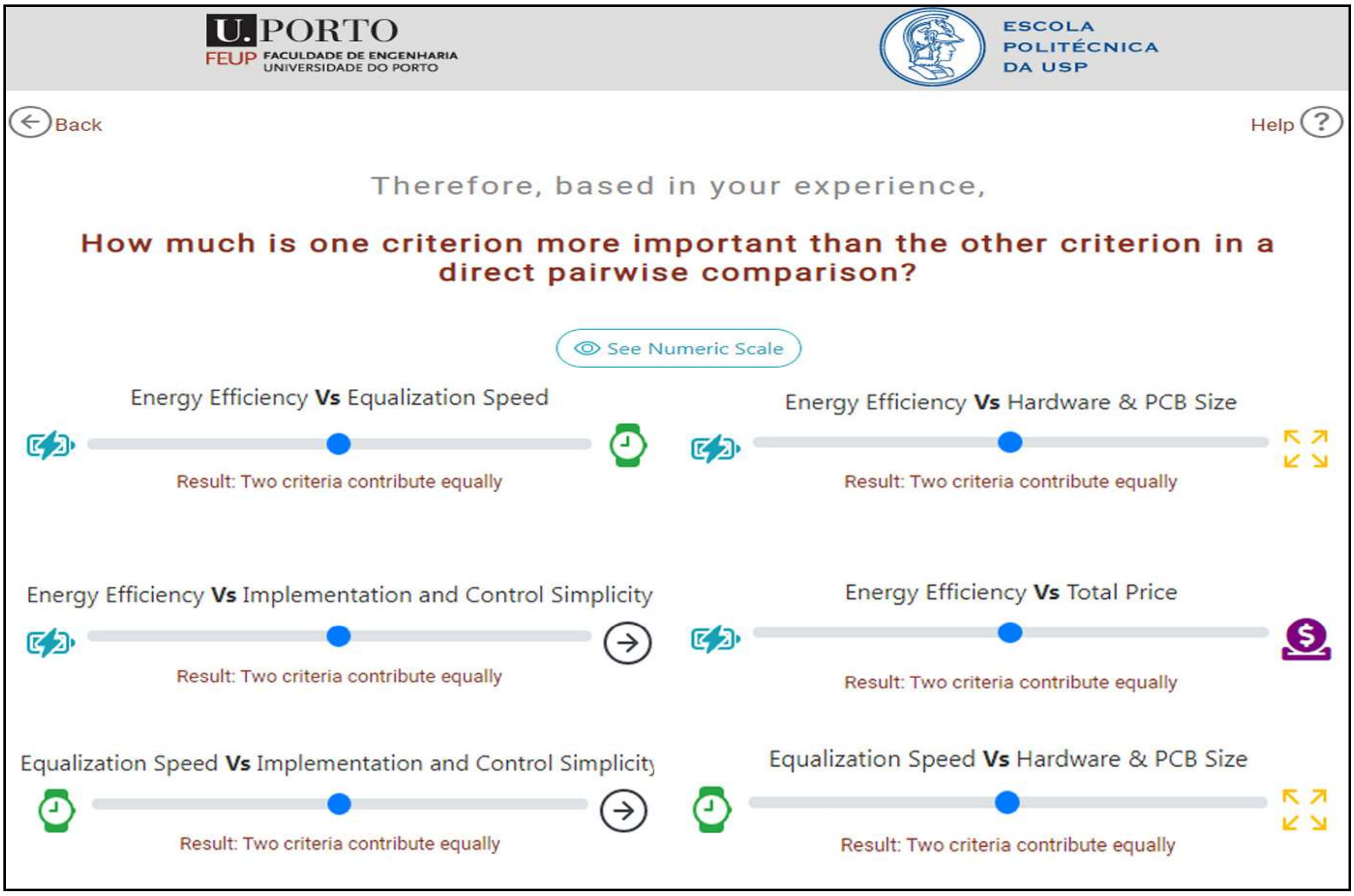


Figure 2. Multiplatform browser application developed to ask and obtain the AHP numerical scale for pairwise comparison matrix A.

Table 4 summarizes the results obtained according to the academic survey research. The displayed results are the mathematical average of all the answers obtained from experts around the world who answered the survey.

Table 4. Survey result for the numerical scale for pairwise comparisons.

Pairwise Comparison	Result	Conclusion and Meaning
Implementation vs. PCB Size	−1.2	Implementation is 1.2 times more important than PCB Size
Implementation vs. Price	2.5	Price is 2.5 times more important than Implementation
Energy Efficiency vs. Implementation	−3	Energy Efficiency is 3 times more important than Implementation
Energy Efficiency vs. PCB Size	−1.8	Energy Efficiency is 1.8 times more important than PCB Size
Energy Efficiency vs. Price	1.7	Price is 1.7 times more important than Energy Efficiency
Energy Efficiency vs. Equalization Speed	−1.5	Efficiency is 1.5 times more important than Equalization Speed
PCB Size vs. Price	2.2	Price is 2.2 times more important than PCB Size
Equalization Speed vs. Implementation	−1.8	Speed is 1.8 times more important than Implementation
Equalization Speed vs. PCB Size	−1.8	Equalization Speed is 1.8 times more important than PCB Size
Equalization Speed vs. Price	2.1	Price is 2.1 more important than Equalization Speed

Table 5 presents the AHP general pairwise comparison matrix A based on the calculation showed in Table 2 and on the survey results presented in Table 4. Red numbers indicate where the survey results were entered in Table 4.

Table 5. AHP Survey general pairwise comparison matrix A result.

Criteria	Energy Efficiency (c_1)	Equalization Speed (c_2)	Implementation Simplicity (c_3)	PCB Size (c_4)	Price (c_5)	Eigenvector (λ)	Weight Vector (W)
Energy Efficiency (c_1)	1	1.5	3	1.8	0.6	1.36	26%
Equalization Speed (c_2)	0.7	1	1.8	1.8	0.5	1.00	19%
Implementation (c_3)	0.3	0.6	1	5.0	0.4	0.57	11%
PCB Size (c_4)	0.6	0.6	1.2	1	0.8	0.79	15%
Price (c_5)	1.7	2.1	2.5	1.2	1	1.60	30%
Criteria vector [Cj]	4.26	5.71	9.50	6.63	3.30	5.34	100%
λ-max	5.15						
MATRIX SIZE (n)	5					**CI**	3.89%
Random Index (RI)	1.11					**CR**	3.51%

Overall, the average results provided by the experts indicate similar levels of importance among the criteria, with pairwise values between 1 and 3 (recall that a score of 1 to 3 suggests an equal or a weak importance of one criterion over the other).

The AHP also produced the following ranking of criteria: (i) price [30%], (ii) energy efficiency [26%], (iii) equalization speed [19%], (iv) PCB Size [15%], and (v) implementation and control simplicity [11%]. As result, price and energy efficiency were slightly more important than the other criteria. It should be noted that since higher energy efficiency usually involves higher costs (e.g., higher engineering hours), it is expected that these two criteria present similar weights. Additionally, given that batteries account for about 25–30% of the price of EVs, it is also expected that the price of battery equalization electronics will play an important role in the selection of the battery equalization system. On the other hand, implementation and control simplicity is slightly less important than the other criteria.

The second part of the survey focused on a comparison of 24 SoC equalization methods to obtain the alternative matrix $\alpha^{(k)} \in R^{n \times n}$ as step 7 at Section 3 demonstrates. Given a specific SoC equalization circuit, the expert was asked to evaluate the energy efficiency (c_1), equalization speed (c_2), and implementation simplicity (c_3) on scale of 1 to 9; the remaining criteria (PCB size (c_4) and price (c_5) were estimated by the authors of this paper, as presented in Section 4.2.

As presented in Section 3, the scale for these criteria is defined as bigger is better for energy efficiency (c_1) and equalization speed (c_2); and smaller is better for implementation effort (simplicity) (c_3), hardware size (c_4), and price (c_5). Figure 3 presents an example of this part of the survey.

After the end of the academic survey research, all the answers were collected and computed into the final result, which represents the opinion of experts from around the world. Table 6 summarizes the obtained results for each equalization method.

Figure 3. Multiplatform browser application developed to ask and to obtain the AHP numerical scale for the energy efficiency, equalization speed, and implementation and control simplicity of the 24 SoC equalization methods.

Table 6. Survey result for the numerical scale for the energy efficiency, equalization speed, and implementation and control simplicity of the SoC equalization methods.

Index—Type	Method	Efficiency (c_1)	Equalization Speed (c_2)	Implement. & Ctrl. (c_3)
1.1 A—Cell Bypass	Cell Bypass	4.6	6.1	3
1.2 B—Cell to Heat	Shunt Resistor	2.3	3.5	2.7
1.2 C—Cell to Heat	Shunt Transistor	4.7	5	3.2
2.1 A—Cell to Cell Shared	Single Switched Capacitor	6	5.5	5.5
2.1 B—Cell to Cell Shared	Single Switched Inductor	5.7	5.1	3.7
2.1 C—Cell to Cell Distributed	Switched Capacitor	5.7	4.9	3.9
2.1 D—Cell to Cell Distributed	Double-tiered Switching Capacitor	6.1	4.6	5

Table 6. *Cont.*

Index—Type	Method	Efficiency (c_1)	Equalization Speed (c_2)	Implement. & Ctrl. (c_3)
2.1 E—Cell to Cell Distributed	Cûk Converter	6	5.8	5.3
2.1 F—Cell to Cell Distributed	PWM Controlled Converter	6.3	5.8	5.3
2.1 G—Cell to Cell Distributed	Quasi-Resonant Converter	6.3	6.3	6
2.2 A—Cell to Pack	Shunt Inductor	5.4	5.3	4.4
2.2 B—Cell to Pack	Boost Shunting	5.8	5.8	4.8
2.2 C—Cell to Pack	Multiple Transformers	6.9	6.8	6.8
2.2 D—Cell to Pack	Multi-secondary Windings Transformer	5.3	5.3	5.7
2.2 E—Cell to Pack	Switched Transformer	5.7	5	4.8
2.3 A—Pack to Cell	Voltage Multiplier	5	6	5.8
2.3 B—Pack to Cell	Multiple Transformers	6.4	5.4	5.1
2.3 C—Pack to Cell	Multi-secondary Windings Transformer	5.8	5.7	4.5
2.3 D—Pack to Cell	Switched Transformer	6.8	5.9	6.1
2.4 A—Cell to Pack to Cell	PWM Controlled Converter	5.7	5.7	6.2
2.4 B—Cell to Pack to Cell	Full-bridge Converter	6.7	6.2	4.7
2.4 C—Cell to Pack to Cell	Bidirectional Multiple Transformers	6.8	5.6	5.6
2.4 D—Cell to Pack to Cell	Bidirectional multi-secondary Transformer	5.7	5.9	5.1
2.4 E—Cell to Pack to Cell	Bidirectional Switched Windings Transformer	5.8	5.8	5

4.2. Hardware Size (c_4) and Price (c_5) Alternative Matrix

The hardware size was defined considering the dimensions of the components required in each equalization method. The price alternative was quantified as a function of the components' costs, engineering implementation work hour, and hardware/PCB size. It is mathematically characterized as:

$$\$_{total} = \$_{elem} + \$_{impl} + \$_{pcb}, \tag{12}$$

where $\$_{total}$ is the equalization method total price, $\$_{elem}$ is the price of the electronic components required to balance 100 cells, which is the average number of lithium cells in series at electric vehicle batteries, $\$_{impl}$ is the engineering implementation costs, and $\$_{pcb}$ is the price of the printed circuit board. To quantify the printed circuit board price and the implementation and control simplicity, the scale was pondered and summed up in Table 7.

Table 7. Price scale applied to the AHP alternative.

PCB Size (Scale)	Price	Implement. & Ctrl. (Scale)	Hours
Small (1)	\$1	Easy (1)	168 h
Medium (3)	\$5	Medium (5)	504 h
Big (6)	\$15	Hard (9)	1008 h
Very Big (9)	\$30	Work Hour Price	\$150

The prices were formulated based on a survey in three big global electronics components suppliers. This survey considered the components capable of handling the balance current of 10 A as assumption number 2 defined in Section 4. Table 8 shows the defined prices applied for every component in this paper.

Table 8. Prices of the main components of the equalization methods.

Components	Price
Switches	$2
Resistors	$6
Transistors	$3
Capacitor	$5
Filters Capacitor	$1
Inductors	$4
Diode	$1
MOSFET	$4
Multi Secondary Winding Transformer	$1000
Winding Transformer	$10
Bi-Directional Transformers	$30
Bi-Directional Multi Secondary Winding Transformer	$1100

The price of the main elements required to balance n cells ($\$_{elem}$) follows the same named relation described in Table 9. The total price of each equalization method to a numerical value into the AHP scale (1–9) is presented in the next section.

Table 9. Equalization method total price steps to convert it in a numerical value on AHP scale.

Index	Engineering Work Hour	Design Costs	PCB Size (c_4)	PCB Price	Main Elements Required to Balance n Cell	Components Price	Total Price	$AHP_{PriceValue}$ (c_5)
1.1 A	336	$50,40.00	3	$5.00	[2n] switches	$400.00	$50,805.00	1.0
1.2 B	302.4	$45,360.00	1	$1.00	n resistors, n transistors	$900.00	$46,261.00	1.0
1.2 C	358.4	$53,760.00	1	$1.00	n transistors	$300.00	$54,061.00	1.0
2.1 A	616	$92,400.00	1	$1.00	[2n] switches, 1 capacitor	$205.00	$92,606.00	5.9
2.1 B	414.4	$62,160.00	3	$5.00	[2n] switches, n filters capacitor, 1 inductor	$504.00	$62,669.00	2.1
2.1 C	436.8	$65,520.00	1	$1.00	n switches, n capacitors	$700.00	$66,221.00	2.6
2.1 D	560	$84,000.00	3	$5.00	[(n/2) + n] capacitors, 2n switches	$1150.00	$85,155.00	5.0
2.1 E	593.6	$89,040.00	3	$5.00	[n] inductors, [2n] switches, [n − 1] capacitors	$1295.00	$90,340.00	5.6
2.1 F	593.6	$89,040.00	3	$5.00	[(2n) − 2] transistors, n inductors	$994.00	$90,039.00	5.6
2.1 G	672	$100,800.00	6	$15.00	[(2n) − 2] transistors, [(2n) − 4] inductors, [n − 2] capacitors,	$1868.00	$102,683.00	7.2
2.2 A	492.8	$73,920.00	1	$1.00	[2n +2] switches, 1 inductor, 1 diode	$409.00	$74,330.00	3.6
2.2 B	537.6	$80,640.00	3	$5.00	[n + 1] switches, [n + 1] diodes, [n + 1] inductors, 1 capacitor	$914.00	$81,559.00	4.5

Table 9. *Cont.*

Index	Engineering Work Hour	Design Costs	PCB Size (c_4)	PCB Price	Main Elements Required to Balance n Cell	Components Price	Total Price	$AHP_{PriceValue}$ (c_5)
2.2 C	761.6	$114,240.00	9	$30.00	[n + 1] MOSFETs, n diodes, 2n inductors, n winding transformers	$2304.00	$116,574.00	9.0
2.2 D	638.4	$95,760.00	6	$15.00	1 multi secondary winding transformer, [n + 1] inductors, [n + 1] MOSFETs	$1808.00	$97,583.00	6.6
2.2 E	537.6	$80,640.00	3	$5.00	2n switches, [2n + 1] diodes, 1 transformer	$611.00	$81,256.00	4.5
2.3 A	649.6	$97,440.00	1	$1.00	n capacitors, 2n diodes, 1 transistor	$703.00	$98,144.00	6.6
2.3 B	571.2	$85,680.00	9	$30.00	1 MOSFET, n diodes, n windingtransformers	$1104.00	$86,814.00	5.2
2.3 C	504	$75,600.00	6	$15.00	1 multi secondary windingtransformer, n inductor, 1 MOSFET	$1404.00	$77,019.00	3.9
2.3 D	683.2	$102,480.00	3	$5.00	1 MOSFET, n diodes, 1 windingtransformer	$114.00	$102,599.00	7.2
2.4 A	694.4	$104,160.00	3	$5.00	n inductors, 2n MOSFET, 1 capacitor	$1205.00	$105,370.00	7.6
2.4 B	526.4	$78,960.00	3	$5.00	4n transistors	$1200.00	$80,165.00	4.3
2.4 C	627.2	$94,080.00	9	$30.00	2n MOSFETs, n bi-dir transformer	$3800.00	$97,910.00	6.6
2.4 D	571.2	$85,680.00	6	$15.00	1 bi-dir multi secondary winding transformer, [n + 1] MOSFETs	$1504.00	$87,199.00	5.2
2.4 E	560	$84,000.00	3	$5.00	1 bi-dir transformer, [2n + 1] switches	$432.00	$84,437.00	4.9

4.3. Alternative Matrix Normalization

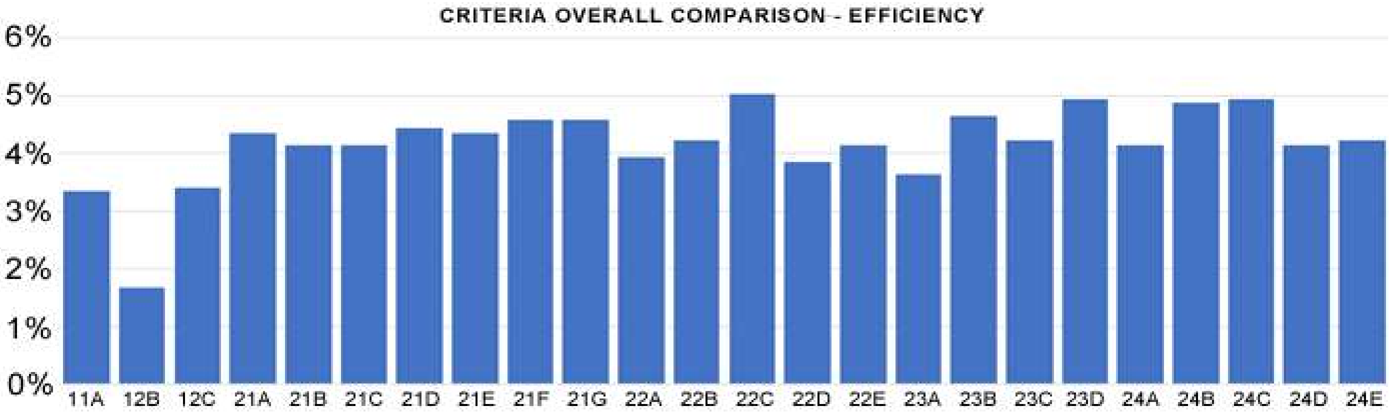
To obtain the numerical value of the AHP scale as a function of the total price of each equalization method and therefore the normalized matrix for all the equalization methods studied in this paper, the total price of each method $\$_{total}$ was subtracted from the lowest price among all of the 24 methods studied in this paper, and it was divided by the maximum price difference from the AHP scale. It is mathematically characterized as:

$$AHP_{PriceValue} = \left(\frac{(\$_{total} - \$_{min})}{(\$_{max} - \$_{min})} \right) \cdot AHP_{maxScale} \tag{13}$$

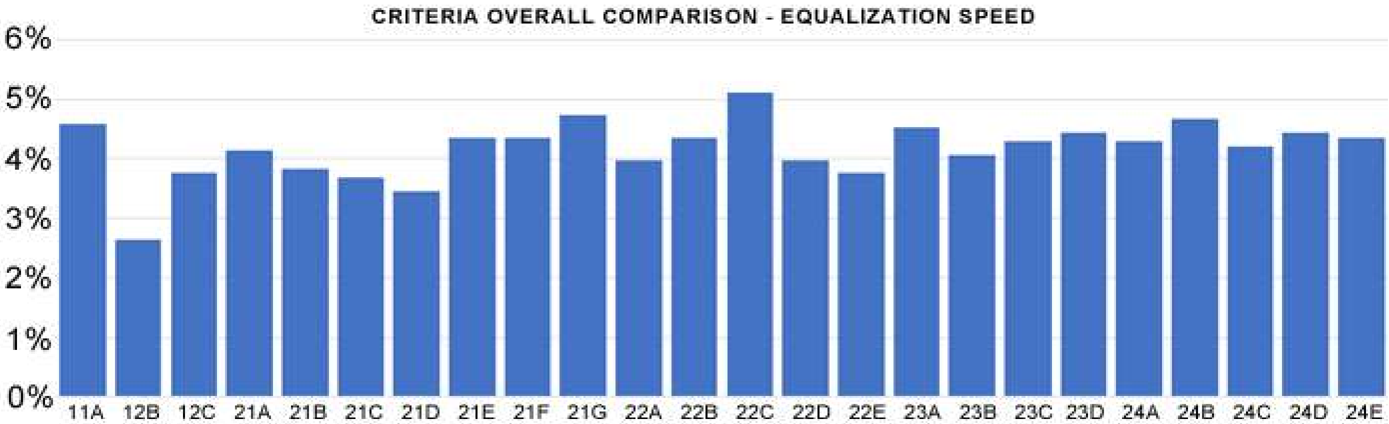
where $AHP_{PriceValue}$ is the criteria $(Price\ (c_5))$ respective method converted total price value for the AHP alternative normalized matrix, $\$_{total}$ is the respective method total price calculated according to Equation (12), $\$_{min}$ is the smallest total price found between all the methods evaluated, $\$_{max}$ is the biggest total price found between all of the methods evaluated, and $AHP_{maxScale}$ is the highest value on the AHP scale. Any $AHP_{PriceValue}$ value smaller than one was rounded to one. Table 9 summed up the steps followed to convert the total price of each equalization method into a numerical value on the AHP scale.

The results presented in Table 9 were obtained considering 1 battery management system (BMS) unit for 100 lithium cells in series. It is important to mention that the price will decrease according to the scale of production.

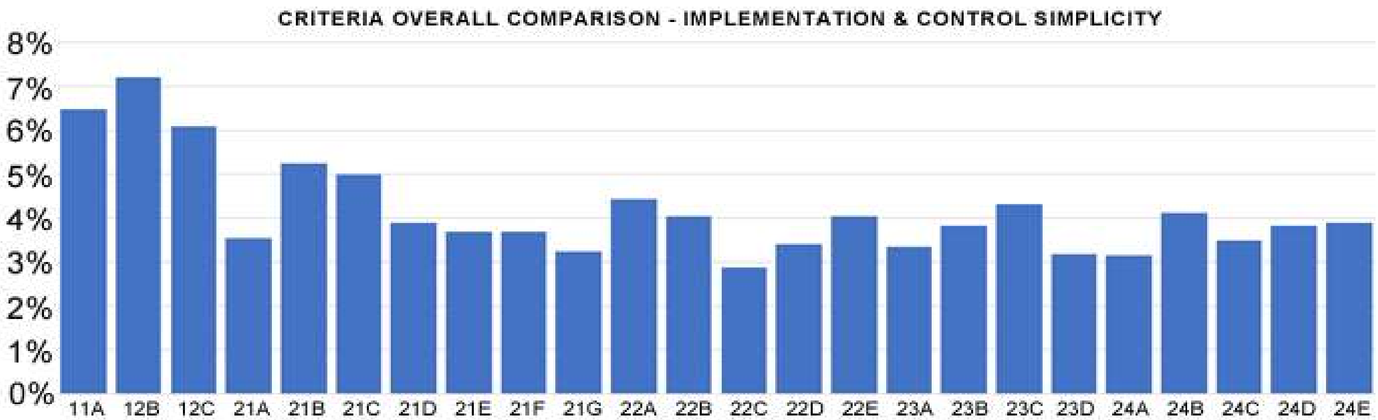
The normalized results—calculated according to Equation (6) or (8)—of all five criteria are presented below in Figure 4, with a comparison between all of the twenty-four evaluated SoC equalization methods.



(**a**)

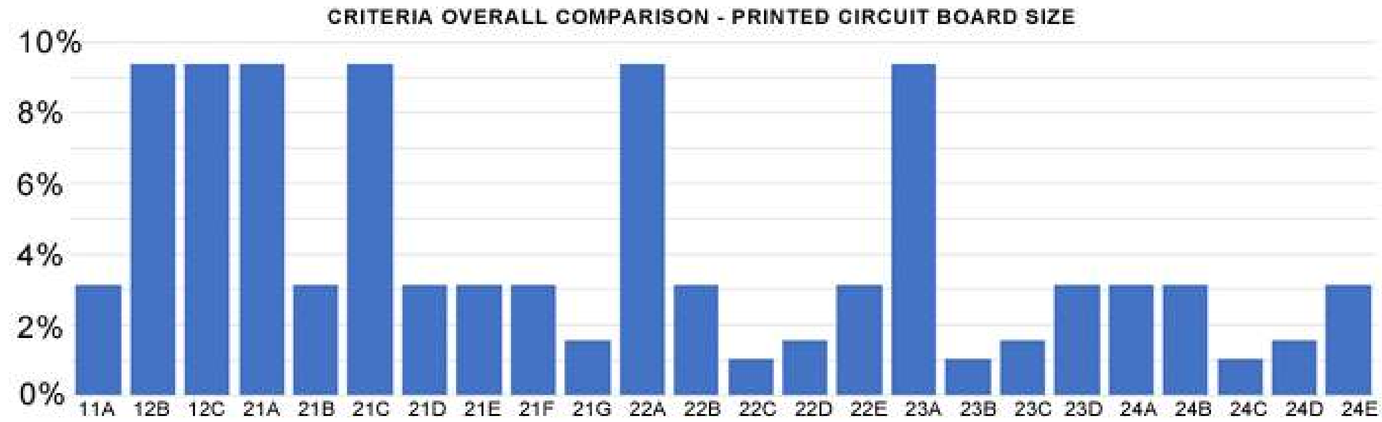


(**b**)

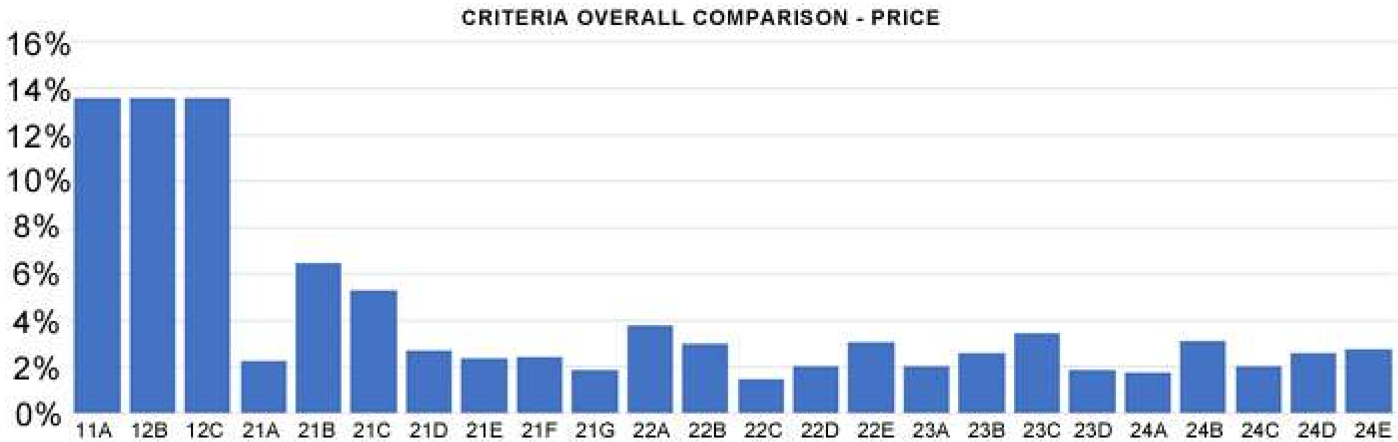


(**c**)

Figure 4. *Cont.*



(**d**)



(**e**)

Figure 4. (**a**) Energy Efficiency normalized result comparison of all twenty-four SoC equalization methods; (**b**) Equalization Speed normalized result comparison of all twenty-four SoC equalization methods; (**c**) Implementation Simplicity normalized result comparison of all twenty-four SoC equalization methods; (**d**) PCB Size normalized result comparison of all twenty-four SoC equalization methods; (**e**) Price normalized result comparison of all twenty-four SoC equalization methods.

4.4. Overall Comparison—Decision Profile Matrix

Taking into consideration all of the requirements and the basic structure from Sections 2 and 3, the authors prepared the decision profile matrix (δ) containing the AHP final decision vector, which is obtained by multiplying the criteria vector (W) by the respective SoC equalization method normalized results of the five criteria according to Equation (11).

The final alternative normalized matrix used in this paper and the overall decision profile matrix (δ) are presented below in Table 10. Figure 5 plots the overall results obtained with the AHP methodology applied in this paper.

Table 10. Decision profile matrix (δ).

Alternative/Criteria		Efficiency (c_1)	Equalization Speed (c_2)	Implement. & Control Complexity (c_3)	PCB SIZE (c_4)	PRICE (c_5)	Decision Vector (δ)
Index	**Weight Vector (W)**	**26%**	**19%**	**11%**	**15%**	**30%**	
1.1 A	Cell Bypass	3.35%	4.59%	6.49%	3.13%	13.58%	6.96%
1.2 B	Shunt Resistor	1.67%	2.63%	7.21%	9.38%	13.58%	7.17%
1.2 C	Shunt Transistor	3.42%	3.76%	6.08%	9.38%	13.58%	7.71%
2.1 A	Single Switched Capacitor	4.36%	4.14%	3.54%	9.38%	2.29%	4.35%
2.1 B	Single Switched Inductor	4.15%	3.83%	5.26%	3.13%	6.47%	4.75%
2.1 C	Switched Capacitor	4.15%	3.68%	4.99%	9.38%	5.32%	5.28%
2.1 D	Double-tiered Switching Capacitor	4.44%	3.46%	3.89%	3.13%	2.73%	3.49%
2.1 E	Cûk Converter	4.36%	4.36%	3.67%	3.13%	2.41%	3.52%
2.1 F	PWM Controlled Converter	4.58%	4.36%	3.67%	3.13%	2.42%	3.58%
2.1 G	Quasi-Resonant Converter	4.58%	4.74%	3.24%	1.56%	1.88%	3.21%
2.2 A	Shunt Inductor	3.93%	3.98%	4.42%	9.38%	3.78%	4.75%
2.2 B	Boost Shunting	4.22%	4.36%	4.05%	3.13%	3.01%	3.70%
2.2 C	Multiple Transformers	5.02%	5.11%	2.86%	1.04%	1.51%	3.16%
2.2 D	Multi-secondary Windings Transformer	3.85%	3.98%	3.41%	1.56%	2.07%	2.96%
2.2 E	Switched Transformer	4.15%	3.76%	4.05%	3.13%	3.03%	3.58%
2.3 A	Voltage Multiplier	3.64%	4.51%	3.36%	9.38%	2.05%	4.14%
2.3 B	Multiple Transformers	4.65%	4.06%	3.82%	1.04%	2.62%	3.31%
2.3 C	Multi-secondary Windings Transformer	4.22%	4.29%	4.32%	1.56%	3.45%	3.62%
2.3 D	Switched Transformer	4.95%	4.44%	3.19%	3.13%	1.88%	3.47%
2.4 A	PWM Controlled Converter	4.15%	4.29%	3.14%	3.13%	1.80%	3.21%
2.4 B	Full-bridge Converter	4.87%	4.66%	4.14%	3.13%	3.13%	3.97%
2.4 C	Bidirectional Multiple Transformers	4.95%	4.21%	3.48%	1.04%	2.05%	3.20%
2.4 D	Bidirectional multi-secondary Transformer	4.15%	4.44%	3.82%	1.56%	2.59%	3.32%
2.4 E	Bidirectional Switched Windings Transformer	4.22%	4.36%	3.89%	3.13%	2.78%	3.62%

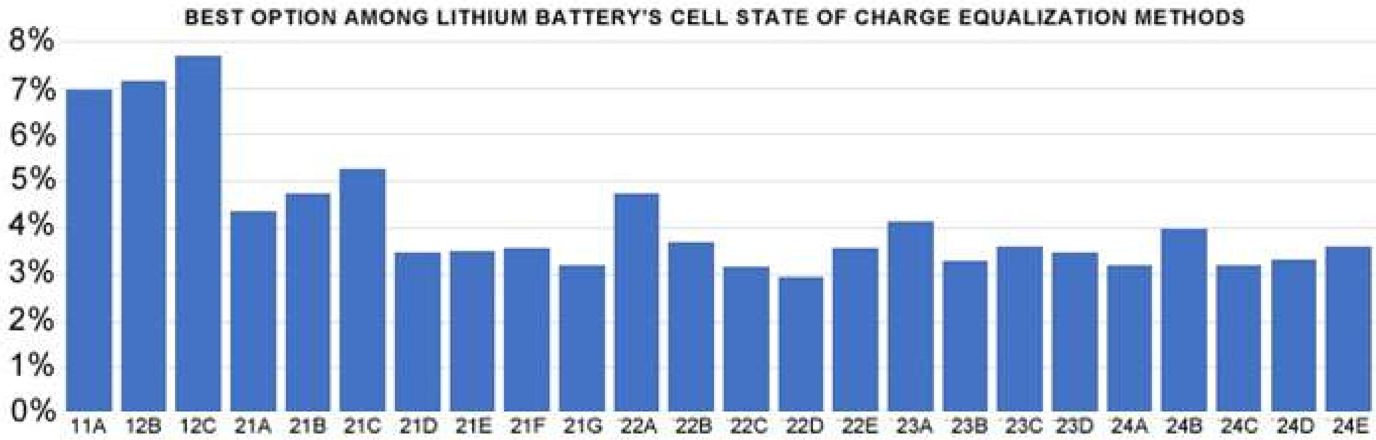


Figure 5. Overall Comparison Matrix of Decision Profile.

4.5. Discussion

The final ranks obtained from the AHP indicate the Cell to Heat—Shunt Transistor method (Index 1.2 C) as the better option considering the five criteria used for the comparison. This method has a satisfactory energy efficiency (normalized score 3.42%), a moderated equalization speed (3.76%), an easy implementation (6.08%), a small hardware PCB size (9.38%), and a low price (13.58%). The other results reveal that energy efficiency and price are the most important and decisive criteria according to data collected from the experts; implementation simplicity, equalization speed, and PCB size play a minor role. Additionally:

- Energy efficiency and equalization speed are very similar across all equalization methods, varying between 3% and 5% (Figure 4a,b). In contrast, PCB size and price present the widest variation. They present values between 2% and 12% (Figure 4d,e). These last two metrics are the main differentiating factors in equalization methods. This result is, in some way, expected as price is usually one of the main factors in industry applications;
- Among all equalization methods, the Cell to Heat—Shunt Resistor (Index 1.2 B) has the worst energy efficiency and equalization speed, although this method has the best implementation and control simplicity;
- Active equalization methods (index 2.x.x) show an average score from 3 to 5% with the math average at 3.72% (see Figure 5), which is significantly less than the passive methods (index 1.x.x) which provide scores > 6.95%. Among active balancing methods, the Cell to Pack—Multi-secondary Windings Transformer (Index 2.2.D) demonstrates the lowest overall score (2,96%), while the Cell to Cell Distributed switched Capacitor method (Index 2.1.C) offers the best (5.28%).

From a cost perspective, the Cell Bypass Complete Shunting (Index 1.1 A), Cell to Heat—Shunt Resistor (1.2 B), and Cell to Heat—Shunt Transistor (Index 1.2 C) present the best prices, which was expected given the low number of electronic components employed in these balancing methods.

5. Conclusions

In this paper, 24 SoC equalization methods were compared in terms of their energy efficiency, equalization speed, implementation and control simplicity, hardware PCB size, and costs. To quantify the relative importance of each design criteria, a survey was conducted with experts from all over the world. The collected expert data was fused with an analytic hierarchy process (AHP) methodology in order to rank the different equalization methods. The results show that the passive methods rank higher due to their low price, small PCB size, and implementation simplicity. Even though active SoC equalization methods have greater energy efficiency and equalization speed, the obtained results demonstrated that these factors do play a less significant role in the selection of equalization methods.

It is important to stress that the experts who answered our survey represent a wide range of geographic areas (Europe, America, Africa, Asia, Oceania) and they may prioritize certain criteria over others depending on where they live and their background (industry vs. academia). Since our AHP approach fuses all of their opinions, this leads to trade-offs between different expert preferences. The authors recognize that this trade-off may lead to sub-optimal recommendations. For example, an equalization method that is better in one part of the world may not be the case in other areas; additionally, academic experts may favor complex and costly balancing options, while industry experts could prefer low cost and simpler solutions. To address this limitation, future work should focus on collecting localized surveys that can target the needs and the preferences of specific geographic areas and users. We also plan to incorporate additional design criteria such as maintenance costs and reliability and validate the results using a dedicated testbench for state of charge equalization.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15072439/s1, File S1: A brief review of 24 battery's cells state of charge (SoC) equalization methods is presented below.

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